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Fifth Edition, PDF Part 2

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FOREST GENETICS

Introduction

Many management practices in forestry, including planting, thinning and harvesting, have the potential to change the local genetic composition of forest trees of a particular species. Any decisions that foresters make to change the number of trees or their population of origin can have genetic consequences for a stand. The active, intentional management of forest genetic resources can improve or maintain forest productivity, while a lack of attention to genetic resources may have negative impacts on forest productivity and other values.

The single most important decision made in forest management with the greatest potential for positive or negative genetic change is the seed source used for reforestation. This choice may impact the genetic makeup of the resulting stand in three ways: 1) **adaptation** of the regenerated trees to the environment of the site, including climate, pests and pathogens; 2) **genetic diversity** of the trees relative to wild stands; and 3) **genetic quality** of the trees for meeting stand objectives for growth rates and wood quality. Provincial forest policy sets criteria for choices of reforestation material (seed or vegetatively propagated plants) to ensure that regenerated forests will be well adapted to the site, have similar genetic diversity to wild stands, and meet fibre production as well as non-timber objectives.

Adaptation

Most tree species of current economic importance in British Columbia (BC) grow across a wide range of environmental conditions. Temperature and moisture vary with location (i.e. elevation, latitude, longitude, distance to the ocean and local topography). Along these broad climatic gradients, local populations of trees within each species are adapted to local (or microsite) conditions. Use of the wrong population for reforestation, just like use of the wrong species, can result in **maladaptation**. In its mildest form, maladaptation results in a slight to moderate loss in growth and wood production, as trees are not ideally suited to site conditions. Severe maladaptation can result in mortality and plantation failure. Maladapted populations are often more vulnerable to insect and disease attacks than local, well-adapted populations, in addition to being more susceptible to abiotic injuries from cold or drought. For example, 'off-site' (maladapted) lodgepole pine suffers more from foliar fungal diseases than local, well-adapted seed sources.

In most species, local adaptation is reflected strongly in the association between environmental temperature variables such as the length of the frost-free period and the timing of the annual growing cycle of trees, from growth initiation (bud burst) in the spring, to cessation of growth in mid to late summer. Trees from milder environments are genetically programd to have a longer period of active growth, and are thus able to grow more in height and diameter per year. As a result, they are usually less cold hardy than trees of the same species from colder environments (e.g. higher elevations, higher latitudes, or less maritime locations). Conversely, trees from colder environments have slow growth but can withstand cold events without injury.

Genetic patterns of variation in traits such as timing of bud burst or cold hardiness that are associated with environmental gradients are called **genetic clines**. The study of the association between genetic clines and environmental variation is called **genecology**. Extensive genecological studies called **provenance trials** have been conducted in BC to determine the steepness and orientation of genetic clines to guide seed transfer.

To establish a provenance trial, seeds are collected from different locations, called **provenances,** throughout a species' range (or portion thereof). Seedlings from different provenances are then grown together in the field, usually in many locations representing different ecological zones. Survival, growth and health are monitored for many years. These results are sometimes supplemented with intensive studies of adaptive traits such as timing of growth or cold hardiness of provenances in short-term seedling nursery genecological experiments. Forest geneticists analyze the data to determine how far seed can be moved from the point of collection to the planting site without risking maladaptation. This is done by first defining geographic **seed planning zones** within which trees are similarly adapted, then by setting allowable maximum seed transfers within SPZs in terms of latitude, longitude and elevation (Figure 1).

Species vary in the degree to which populations differ genetically. For example, lodgepole pine and Douglas-fir are adaptive specialists, with a high degree of population differentiation and steep genetic clines. Western white pine and western redcedar are adaptive generalists, species whose populations do not differ much. As a result, seed transfer guidelines are more restrictive for lodgepole pine and Douglas-fir, particularly for elevational transfer distances, than for western white pine and western redcedar. For example, seed collected from natural stands of western white pine can be transferred up to 700 m in elevation up or down from the site of collection to the planting site, while lodgepole pine south of 56°N latitude can be transferred up 300 m or down 100 m from the planting site (BC Ministry of Forests, 1995). Seed transfer guidelines often allow greater seed transfers from warmer to colder environments (e.g. from south to north) than the reverse based on results from provenance trials that show populations from slightly milder environments often have greater growth rates and comparable survival and health relative to local provenances.

In the absence of genecological information, using a local seed source is the choice of lowest adaptational risk, but provenance trials sometimes indicate the relative superiority of specific non-local provenances over local provenances within a region. Seed collected from wild stands is called genetic **Class B** seed in BC. Seed collected from **superior provenances** identified in provenance trials is called **Class B+**. Superior provenances, identified in seed use policies of the BC Ministry of Forests, have greater maximum transfer distances than Class B seed, Lodgepole pine has numerous B+ provenances identified as having superior growth. The Haney and

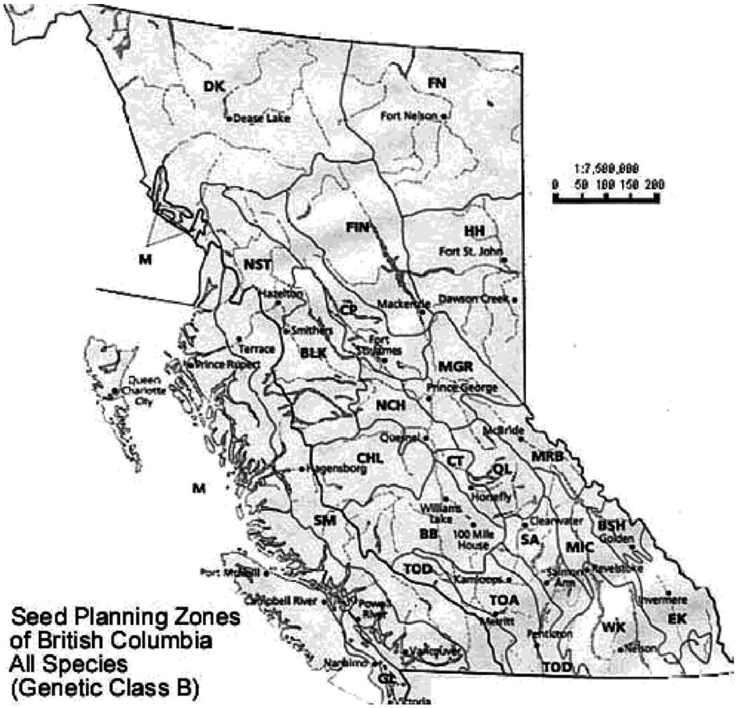

Figure 1:
Seed planning zones in British Columbia for seed collected from natural stands (genetic Class B seed) for all species. Species-specific latitudinal, longitudinal and elevational limits control movement of seed within zones from the collection location to the site to be reforested.

Big Qualicum Sitka spruce provenances have higher levels of resistance to the white pine shoot tip weevil (*Pissodes strobi*), a pest of major economic importance, and are thus designated as sources of B+ seed. For genetically improved seed collected from seed orchards (**Class A**), there are separate seed planning zone maps for each major commercial species.

Seed transfer guidelines ensure that seed collected for reforestation is adapted to the site on which it is used. **Genetic diversity** is maintained through standards specifying the minimum number of trees from which seed must be collected for a Class B or B+ seedlot. At least twelve trees must contribute to the seedlots, and many different pollen parents will have pollinated the seed collected from each seed parent.

When natural regeneration is used in reforestation, the choice of provenance is not an issue as trees on or near the site produce the seed. However, genetic quality and genetic diversity must be addressed. Adequate numbers of trees must be left as seed parents to provide sufficient genetic diversity, and to produce sufficient amounts and movement of pollen between trees to ensure that the seed produced does not result from self-pollination or matings (crosses) among related trees. To maintain genetic quality, it is important that leave trees remaining after partial cutting have desirable characteristics in terms of health, form and growth rate. If only slow-growing, crooked or diseased trees remain as parents of the next generation, it is likely that the quality of the resulting stand will be lower than if high-quality seed parents are left.

Forest Genetic Resources and Tree Improvement

The genetic quality of reforested stands can be improved considerably when stands are regenerated using planting stock produced through selective breeding. Seed obtained from parent trees selected in a **breeding program** and collected in a **seed orchard** containing such parents is called genetic **Class A** seed. The selected trees are planted in an area called a **seed orchard**, and become the **production population.** A seed orchard is a plantation that is intensively managed for frequent and abundant seed production. Seed orchards are commonly established in areas with good history of seed production, close to water, infrastructure, and labour.

Breeding programs range from being simple to very complicated. In most cases, the breeding method, the trait(s), and the short- and long-term goals of the program determine the level of sophistication. Most tree breeding programs share several steps in common: **selection**, **breeding** and **testing** (Figure 2). Selection is the act of choosing individuals that will serve as parents in the breeding program. Parents are either selected for their apparent superiority – **phenotypic selection** (individuals are selected based on their appearance), or based on their performance

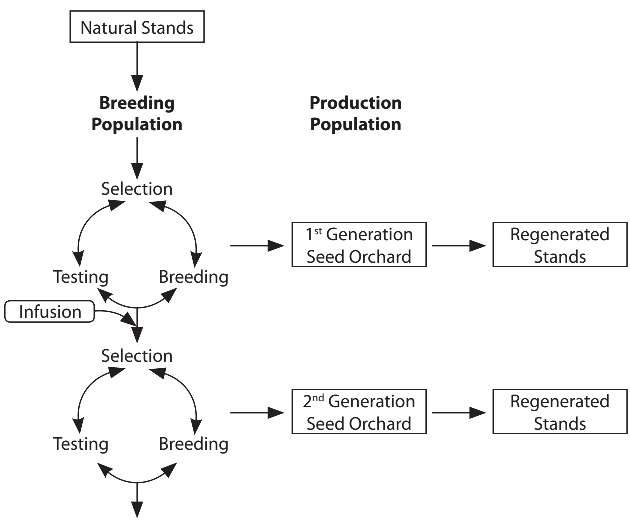

Figure 2:
The progression of a breeding program: from selecting trees in natural populations, through successive breeding cycles, incorporating new wild selections after each cycle (infusion) and creating production populations (seed orchards).

in the field or their offsprings' performance (i.e. individuals are selected based on tested genetic traits) – **genotypic selection**. As the breeding program advances from one generation to the next, the selection of parents is mainly based on their true genetic potential, or genetic worth. After the successful selection of parents, these parents form the **breeding population**. Individuals within the breeding population usually are mated in a specific **mating design** to produce families for testing. Families can be half-siblings, where seedlings share a maternal, or seed-cone parent and are pollenated by an uncontrolled mixture of male parent trees; or full-siblings, where seedlings share both pollen and seed-cone parents as a result of controlled pollination. The use of repeated selection cycles is called the **recurrent selection system**.

After each breeding cycle is completed, superior individuals are identified and are either grafted or planted as rooted cuttings in seed orchards. The selection of superior individuals for inclusion in seed orchards is done through forward or backward selection or a combination of the two. **Backward selection** is the selection of the best parents (**plus-trees**) based on the performance of their offspring. **Forward selection** is the selection of the best individual from the offspring of a particular cross. Backward selection provides the breeder with some assurance of the selected tree's performance while forward selection is less certain since performance of the tree's offspring cannot be predicted exactly. While less expensive and easier to achieve in the short-term, backward selection is an adaptive dead end, since maximum improvement has already been attained by selecting individuals. Forward selection offers a great deal of room for further improvement through continued breeding and testing. Most breeding programs use a combination of these two selection methods.

Tree breeding follows the same basic principles applied in most genetic improvement programs such as corn, wheat, milk or egg production but with slight modifications that accommodate the generation length, the ease or difficulty of breeding, and the ability to produce sexual (seed) and asexual (rooted cuttings and/or clonal seedlings) material for field testing. Thus intensive breeding should be considered a tool to attain substantial economic gain and increase yield as well as adaptation. The degree of genetic variation is considered to be the most important prerequisite for success in any breeding program. The careful selection of individuals that will serve as parents in the breeding program will set the stage for the level and magnitude of improvement that can be acheived.

For seed orchard populations to attain maximum genetic gain, they should act as closed, perfect populations. Several biological prerequisites are required for this: isolation from contaminating (unimproved) pollen, reproductive synchrony (all seed orchard trees shed and receive pollination simultaneously), and output equality (all parents produce the same amount of pollen and seed). These conditions are seldom met, but most of these shortcomings can be overcome with proper seed orchard management techniques.

Testing is often conducted on sites within the provenance of the parent trees, called the **breeding zone**, and follows a very strict set of rules and a variety of experimental designs. These rules are needed to properly evaluate the genetic worth of the selected parents. These include: number of test sites within the breeding zone, number of replications, number of offspring representing a family or cross, site environmental parameters, and a regular maintenance and assessment schedule.

Selected parents' genetic worth is often determined by the performance of their offspring, so it is important to invest time and money during the testing phase to control the quality of the results.

Various quantitative models are used to calculate the genetic parameters of each attribute selected for. These parameters determine the level of genetic control over these attributes (**heritability**), the extent of genetic and environmental influence over the trait under selection (**genotype-by-environment interaction**), the direction and magnitude of the genetic clines and relationships among traits, and the rate of genetic improvement with breeding. This process is continuous and advances from one generation to the next (Figure 2).

Balancing a breeding program's short- and long-term goals ensures breeders and forest populations can rapidly adjust to unanticipated future events. **Short-term** goals focus on the degree of improvement over unselected sources and minimizing inbreeding to avoid any detrimental effects. **Long-term** objectives focus on program flexibility, the rate of breeding generation turnover, and the maintenance of genetic diversity in the breeding population. Short- and long-term objectives must be combined to optimize both success and flexibility.

The delivery of genetically improved seedlings for reforestation is a continuum of activities that should work in synchrony to ensure the genetic gain captured by tree breeders is delivered to field foresters. Figure 3 demonstrates a typical tree improvement delivery system. Biological issues that may decrease genetic gains throughout the system include factors in orchard location and design, as well as seed aging and germination. When a seed orchard crop is harvested and processed

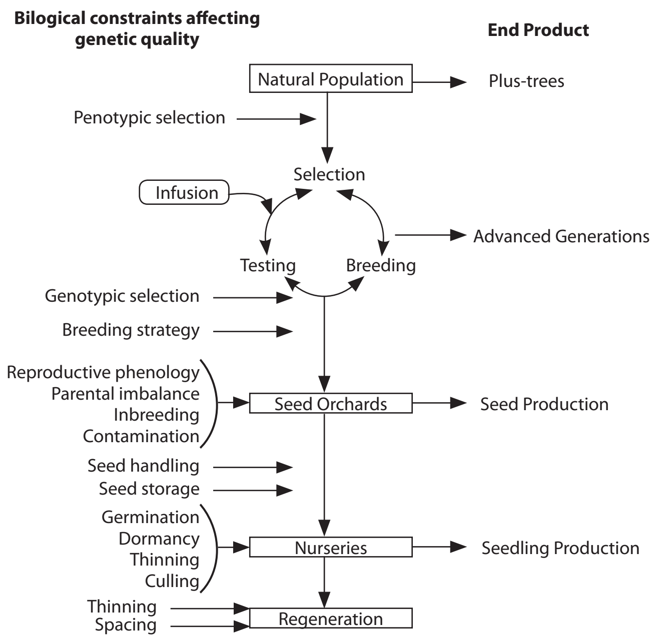

Figure 3:
Schematic diagram of forest tree domestication featuring the major steps of a tree improvement program.

Table 1: Summary of species under genetic management by the BC Ministry of Forests (by 2003)[a].

	Species[b]	Provenance/ genecology	Progeny trials[c]	# orchards	Seed planning zones represented[d]	Breeding program objectives (in order of importance)
Coast	Ba	Y		1	M	Trial orchard only
	Bg	Y		1	M	No longer managed
	Bn	Y			M	
	Cw	Y	2, 3	5	M, SM	Growth/yield
	Dr	Y			various	
	Ds	Y			various	
	Fdc	Y	1, 2, 3	11	M, SM	Growth/yield, wood density, stem form
	Hm	Y			M	
	Hw	Y	1, 2	6	M	Growth/yield, wood density, stem form
	Maple	Y			various	
	Poplar	Y			various	
	Pw	Y	1	3	M, SM	White pine blister rust resistance/tolerance, stem form, wood quality
	Ss	Y	2	1	M	Shoot tip weevil resistance/tolerance, wood quality, stem form
	Sx/Ss	Y	1, 2, 3	5	M, SM, NST	Shoot tip weevil resistance/tolerance, wood quality, stem form
Interior	Yc	Y	2, 3	4	M	Growth/yield, wood quality, stem form
	At	Y			various	
	Bl	Y			various	
	Ep	Y			various	
	Fdi	Y	1, 2	7	NE, PG, EK, QL, CT	Growth/yield
	Lw	Y	1, 2	2	NE, EK	Growth/yield, wood density
	Pli	Y	1, 2	22	NE, PG, CP, BV, EK, TO	Growth/yield, wood density
	Pw	Y	1	2	KQ	Shoot tip weevil resistance/tolerance, stem volume
	Sx/Se	Y	1, 2	19	NE, TO, BV, PG, PR, EK	Growth/yield, wood density, shoot tip weevil resistance/tolerance

[a] Source: Forest Genetics Council 2002/2003 Annual Report, Forest Genetics Council 2002/2003 Business Plan; Ministry of Forests Tree Improvement Branch.
[b] Species codes assigned by BC Ministry of Forests.
[c] 1 = 1st generation; 2 = advanced generation; 3 = clonal orchards.
[d] M = maritime; SM = submaritime; NE = Nechako; PG = Prince George; EK = East Kootenay; BV = Bulkley Valley; PR = Prince Rupert; TO = Thompson-Okanagan; CP = Chilcotin plateau; NST = Nass-Skeena transition; QL = Quesnel; KQ = Kootenay Quesnel.

as a bulked seedlot, it usually receives one storage treatment and one germination treatment (e.g. stratification). These bulk seedlots represent various parent trees. Seed from different parents often respond differently to these treatments. This could have an unintentional **directional selection** effect during the seedling production phase, like inadvertently selecting for early germination, since later germinants may be culled.

Tree Improvement in BC

In BC, several species are in intensive breeding programs and significant genetic gains have been achieved. Breeding programs for increased growth and yield, adaptation, wood quality, and resistance to pests are in progress for coastal and interior species. Breeding programs in BC are typically combined with preliminary studies of genetic diversity, particularly provenance tests. Table 1 lists all the species currently in breeding programs, within a program co-ordinated by the Ministry of Forests, in consultation with the Coastal and Interior Technical Advisory Committees. Species selection for breeding is generally based on the market value of the species, planting need, expected productivity, and the impact of pests.

Seed collected from each parent tree, both wild and orchard, is identified with a unique seedlot number. The **Tree Seed Centre** (TSC) serves as a centralized handling, processing, distribution, and storage depot for all seedlots collected in BC and is managed by the BC Ministry of Forests. The **Seed Planning and Registry** system (SPAR) (www.for.gov.bc.ca/hti/spar/index.htm) is a central online platform for seedlot information, accession and planning. Detailed information on each seedlot available through this system includes genetic gain, breeding history, test results, and guidelines for seed transfer. To obtain access to SPAR and associated tools, you must register online to obtain a secure ID code.

Other services provided by the Tree Seed Centre include seed storage, testing and quality assurance. Methodology follows standardized international rules established by the International Seed Testing Association (ISTA). These include the use of standard tests to determine seedlot attributes such as moisture content, purity, weight, and germination rate. These tests are repeated every 1 to 4 years, depending on species, to monitor and adjust calculations for the effects of storage.

To order seed, a request for seed sale or transfer is submitted to the TSC, requiring the seed owner's written authorization. This request is entered onto SPAR. Seedlots can be entered under two categories: reserved, which can be accessed only by the seed owner, and surplus, which can be obtained by submitting seedling requests (SRQ). Seedlots require a purchase agreement with the seedlot owner prior to approval of the SRQ. For each transaction, the TSC prepares and forwards written confirmation to the seller and purchaser when the transaction is complete on SPAR. Seed withdrawal requests are filled to meet sowing dates requested by the client, including current-year cone collections, providing there is sufficient time to prepare and transport the material.

Forest Genetics and Biotechnology

Genetic markers and their use in forestry

Genetic markers are visible products of small, genetically variable segments of DNA. They are useful for several applications in forestry, such as characterizing species diversity, identifying patterns of seed and pollen flow, and measuring inbreeding. Reflecting the many possible effects of mating and evolution on DNA sequences, and the variety of techniques to assay these differences, there are several types of genetic markers (Ritland and Ritland, 2000).

Types of markers

Why do we need markers? Markers provide a means by which two or more apparently similar individuals (**phenotype**) can be characterized using protein and/or DNA fingerprinting (**genotype**). Markers are either **dominant** or **co-dominant.** Forest plants and animals have 2-stranded DNA in each cell, where there are two complete copies of each molecule and gene. The copies can be the same, or different, since one copy comes from each parent. Dominant markers only show cases where a gene sequence is present (a band will appear) or absent (nothing will appear). Dominant markers do not differentiate between individuals which are homozygous (with 2 identical copies of a gene, or **alleles**) and heterozygous (with 2 different alleles), but co-dominant markers will show both alleles.

Protein markers, called **isoenzymes** or **isozymes**, show bands on a gel surface indicating multiple alleles of an enzyme, which are products of genes that differ usually in one or more amino acids. As they are inexpensively assayed and easily developed for any species, they are very popular codominant genetic markers. All other markers are directly based upon specific portions of DNA, copied many times by enzymes in the **polymerase chain reaction** (PCR). PCR can replicate portions of a DNA sequence up to a billion times the initial quantity, enabling less invasive testing for organisms and the environment. One inexpensive DNA marker known as **RAPD**s (Random Amplified Polymorphic DNA) is used to assess genetic diversity based on random DNA fragments. **AFLP**s (Amplified Fragment Length Polymorphism) are similar to RAPDs in that both markers are dominant, but AFLP targets short known DNA sequences. **Microsatellite** markers are codominant, representing a stretch of DNA where a specific short pattern is repeated many times. The number of repeats (each repeat is one allele) can be extremely variable. Most organisms are heterozygous for microsatellite markers.

Sampling

The isozyme technique requires fresh, living tissue, as this is where enzymes are most abundant. In trees, these include freshly germinated seeds, vegetative buds, or young leaves. After sampling, tissue should be kept on ice, then ground up in a special buffer that prevents protein damage. For DNA markers, a much wider range of material can be used. Most parts of a tree (needles, pollen, seeds, bark, xylem, roots, etc.) can be used; even dried plant material, herbarium specimens, or well-preserved fossilized material can be used. In animals, hair follicles and scat can be tested for non-invasive assays of wild populations. Samples can be kept temporarily at room temperature in the appropriate solution (usually alcohol) until DNA extraction.

Marker applications

1. ***Identification of cultivars, seedlots, populations and species***
Markers have been used extensively to identify and distinguish cultivars in many agricultural and horticultural crop species. Microsatellites are particularly useful for identification and analysis for management purposes. The highly heterozygous genotypes of most forest trees makes distinction of varieties difficult to impossible. Markers can identify distinct populations and hybrids, useful for breeding zone delineation.

2. ***Characterization of genetic diversity, population structure and gene flow***
Markers provide baseline information about levels of genetic variation within species, and hence the adaptability of a species, its potential to achieve gains from breeding, and to develop effective gene conservation strategies. At least 20-30 individuals per population should be sampled for effective analysis. There are many computer programs to analyze and interpret the data.

3. ***Studies of the genetic efficiency of seed produced from seed orchards***
Seed orchards have three main factors affecting genetic efficiency: self-pollination (**selfing**), pollen contamination from trees outside the orchard, and parental imbalance, where some trees produce a disproportionately large or small amount of pollen or seed. Markers can be used to measure selfing by comparing the genetics of parent trees and their offspring. For accurate estimates, hundreds of progeny from several mother trees are necessary. While most conifers have negligible selfing, western redcedar can have up to 50%, which can affect seed quality due to inbreeding effects. Pollen contamination and imbalance are better studied with DNA markers such as microsatellites, as they are more likely to differentiate at such fine scales.

4. ***Verification of crosses and marker-assisted breeding***
Controlled crosses can be mislabeled or contaminated by foreign pollen. Markers can verify the parentage of controlled crosses and ensure efficient breeding progress.

Genomics

Genome research involving the entire DNA sequence of an organism (genomics) is a relatively new discipline in life sciences. Genomics aims to achieve the most comprehensive understanding of the genetic blueprints of living organisms. Genome research addresses structural aspects of genomes, which is the complete genetic material (DNA) of an organism, as well as how the information encoded in the genome is translated into cellular and biochemical processes. Genomics and its practical applications are rooted in the combined technical revolutions of computer sciences applied to biology (**bioinformatics**) and high-throughput automated processes for DNA sequencing, gene expression profiling, genotyping, protein profiling, protein identification (**proteomics**, comprehensive analysis of proteins) and metabolic profiling (**metabolomics**). The term genomics is often used inclusive of proteomics and metabolomics. Genome research addresses the structure of genomes, as well as functional aspects of how the encoded information in DNA directly and indirectly affects organisms. The terms **structural genomics** and **functional genomics** are commonly used, although they sometimes overlap.

Understanding the detailed sequence, organization and function of tree genomes has the potential to accelerate the tree improvement cycle by directly selecting superior breeding stock. There are many other potential applications of genomics in forestry. For instance, genomics can support our knowledge of ecosystem biodiversity, provide new tools for monitoring forest health, and enable us to understand more about forest adaptation to changing environments, such as those predicted due to global climate change.

Genome sequencing identifies the precise order of each component nucleotide (abbreviated A, C, G, and T) in the DNA of an organism. Complete genome sequencing first identifies the order of nucleotides in many small fragments of DNA, which are then compiled using computer software. Conifer genomes are very large, many times larger than angiosperms like poplar, which has had its complete genome sequenced. No conifers will be sequenced in the immediate future, due to their tremendously large and complex genomes.

It is often easier and more efficient to obtain DNA sequences only for the parts of a genome that can be translated into proteins. The proteins have specific functions. To obtain the DNA sequence, the RNA which is the transcribed product is copied back into its DNA complement (**cDNA**). This cDNA is exactly and only the expressed genes, which are archived in **cDNA libraries**. Sequencing cDNA molecules or parts of them provides sequence identification of expressed genes. These sequences are referred to as Expressed Sequence Tags (**EST**s). This technique has been applied so far to tree species with relatively small genomes (e.g. poplars) as well as species with very large genomes (e.g. conifers). Large-scale EST programs are underway for tree species including poplars, pines and spruces.

Single Nucleotide Polymorphisms (**SNP**s), single nucleotide differences, are the smallest possible variations in genomes. They can be used to distinguish individuals of the same or closely related species. If associated with phenotypic traits, SNPs can provide useful genetic markers for selecting and breeding for desirable traits such as wood quality or pest resistance.

Gene expression profiling is the simultaneous analysis of the expression of hundreds or thousands of genes in an organism or tissue. This technique aims to identify sets of genes which are regulated together. By using microscopic samples of cDNA or fragments called **microarrays**, researchers are now identifying changes in gene expression during wood formation and many other traits. **Protein expression profiling** is similar to gene expression profiling, but uses 2-dimensional gel electrophoresis or chromatography to discover complete sets of proteins associated with specific traits or developmental stages. **Metabolic profiling** identifies molecules or compounds associated with desirable traits or features such as superior wood quality, tolerance or resistance to pests, nutrient status, or the effects of environmental stress on forest tree adaptation. This technique may lead to the discovery of new medicinally active compounds such as the anticancer drug taxol found in yew trees. Today, taxol and related pharmaceuticals have a multi-billion dollar annual market value.

Genomic research is now beginning to accelerate our knowledge of fundamental tree biology. Up-to-date information about this rapidly developing field is widely available on the World Wide Web. Genomics of forest trees *per se* does not require the genetic manipulation of trees. Although certain techniques in functional genomics use plant transformation (inserting short DNA fragments into a targeted DNA sequence) as a research tool, *no genetically modified trees are deployed in BC*, and there are no plans to do so.

Somatic embryogenesis

The ultimate goal of any tree improvement program is to maximize the genetic gain per unit time and/or area. Traditionally, seed orchards have been the factory where the genetic gain was packaged and delivered to nurseries to produce improved seedlings needed for reforestation. Wind-pollinated seed orchards have occasionally fallen short of expectations, prompting some breeders to make elite crosses (crosses between the best seed orchard parents) for seed production, followed by vegetative or clonal propagation to produce more seedlings with high genetic gain. This approach made **family forestry** (planting large areas with seedlings from one or more crosses) feasible. The time and expense required for **serial propagation** (multiple cuttings taken off a single cutting) is thus offset by the additional gain. Within-family genetic variation can not be assessed or evaluated using family forestry since by the time comparisons can be made, the trees will have aged, decreasing the quality of the plants and subsequent cuttings. A new tissue culture technique called **somatic embryogenesis** (SE) offers an opportunity to overcome some of these limitations and providing the most viable option for practicing clonal forestry.

Conifers can be vegetatively propagated in three ways: **macropropagation** (rooted cuttings), **micropropagation** (organogenesis, where tissue is cultured on a petri dish into a whole plant) and **gametic** or **somatic embryogenesis**. Macropropagation is widely used in a variety of species, such as spruces, radiata pine and yellow-cedar but depends on the availability of juvenile material. Micropropagation involves treating tissue with growth regulators to induce bud or shoot formation, but success varies with species and tissue age. SE produces embryos vegetatively without seed coats from plant tissues in the lab. Immature embryos from elite crosses are used to mass produce copies of themselves. Due to genetic recombination during sexual reproduction, each line of embryos must be field tested since not all embryos from these superior crosses will themselves be superior.

Importance of clonal testing

Genetic segregation and recombination among genes during meiosis are key processes in sexual reproduction. They are the mechanisms responsible for the genetic similarities and differences among individuals within a family. That is why brothers and sisters differ in their attributes. When elite parents are crossed in a tree improvement program, the offspring are expected to differ from each other, exhibiting within-family variation. In clonal forestry, the cloning process can provide the maximum attainable genetic gain since none is lost to further genetic recombination. The embryos within different seeds from a cross can be tested to determine their performance, and the best ones cloned for mass production of seedlings (amplification), where thousands or hundreds of thousands of copies are produced for reforestation. The number of crosses and the number of clones within each cross are important to ensure adequate levels and distribution of genetic variation across the landscape are maintained (El-Kassaby, 2001).

Implementation of SE

SE should be used to augment traditional tree improvement delivery systems and not as a replacement. High genetic gain clones should be planted on high productivity sites, allowing the production of more fibre from less land. Clones with high pest or disease resistance can also be produced through SE. Consistent levels of disease or pest resistance in parents often cannot be conferred directly to offspring through sexual reproduction, or even rooted cuttings after sexual reproduction, due to complex genetic control and genetic recombination. SE can also be utilized in the testing phase of breeding programs to increase sample size of progeny for more accurate data analysis.

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Forest Protection

FIRE ECOLOGY AND MANAGEMENT

by

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FIRE ECOLOGY AND MANAGEMENT

The value and importance of the forest and range resources and related industries to British Columbia resulted in fire prevention laws which are now over 125 years old. The organized suppression of wildfires began in 1905 and over the decades has experienced vast technological and methodological improvements. Our knowledge of the natural role of fire and its beneficial and deleterious effects has improved markedly since 1905, and primarily during the past 40 years.

Fire ecology is more of a science, while fire management is both a science and an art. It does not take place in isolation of society, society's values or resource management objectives. As it has for the past few decades, fire management includes both appropriate fire control and appropriate fire use.

Fire Ecology and Types of Fire

Fire ecology is "the study of fire as it affects and relates to the natural environment and the interrelationships of the plants and animals therein" (CIFFC, 2003). Fire takes several forms and results in a wide range of ecological effects in space and time. Forest fires are classified as ground, surface or crown fires. Ground fires slowly consume the organic soil layers and, because oxygen is in short supply, combustion is slow and flames are absent or small. Surface fires burn the combustible material lying above the duff layer, between the ground and ladder fuels (CIFFC, 2003). These fires consume twigs, branches and coarse woody debris on the forest floor as well as herbaceous plants, shrubs and small trees. Flame lengths vary from about 30 cm to several metres and may reach into the overstorey tree canopy.

Crown fires advance through the crown fuel layer, usually in union with a surface fire, and are the most impressive of all forest fires, especially when aided by strong winds, steep topography, or both. Crown fires can be described in terms of their dependence on the surface fire. An intermittent crown fire is one in which trees torch sporadically, with the rate of fire spread determined by the surface fire. Active crown fires propagate as an established wall of flame that extends from the forest floor to above the crown fuels. An independent crown fire advances in the crown fuel layer only. Crown fires may travel as quickly as 200 m per minute and have flame lengths up to 200 m.

The behaviour of a fire can be described as smouldering, creeping, running, torching, spotting or crowning (CIFFC, 2003). Variations in type of fire (ground, surface or crown) and behaviour make each fire a unique event. The combination of frontal fire intensity (Byram, 1959; Alexander, 1982) and residence time, which is the length of time required for the flaming zone to pass a given point, determines a fire's ecological effects. At a broader scale the ecological effects, fire sizes and fire frequencies determine the landscape patterns – from a mosaic of small patches of different ages resulting from frequent fires to large patches representing a few significant fire events.

Fire History

Evidence of historic forest fires exists as fossil charcoal, charcoal layers in aquatic sediments and soil horizons, unique stand age structures, burned standing dead trees and downed coarse woody debris, charred live trees, fire-scarred live and dead trees and historical records and photographs. Fire history studies in British Columbia have determined that fire has influenced most of our forests and grasslands over millennia.

The fire history of a particular area is related to a number of environmental factors such as climate (general and drought periodicity), aspect (warm versus cool), elevation (related to microclimatic variations and lightning incidence), topography (fire behaviour and burn patterns), fuel types (rate of spread and fire intensity) and ignition probability (lightning and human).

Wildfire size is determined by fire behaviour, which is a function of the number of ignition points, fuel quantities, fuel arrangements and availability for burning (due to moisture content) as well as terrain features (e.g. natural firebreaks or barriers to fire spread), topography, wind speed and wind directions (determinants of a fire's rate of spread and direction of travel). A fire event creates a unique pattern, ranging from a burned patch within an unburned landscape to a burned landscape containing unburned patches. Recurring fires modify these patterns.

Fire reports maintained by the BC Forest Service estimate that 11,207,000 hectares were burned by 181,000 fires from 1912 to 2004. This is an underestimate because many large fires of the early 1900s were not detected or recorded. However, other areas burned more than once during the period of record, especially in the grasslands and dry interior forests. Wildfire sizes have ranged from small spots to 100,000 to 200,000 hectares, or more, and have a size-class distribution with a large number of very small events (< 1 ha in size), a small number of very large events (> 100,000 ha) and a continuous size distribution in between. The largest fires often result from a combination of multiple ignitions, extensive and dry forests, gentle to moderate topography and strong winds.

Of the 20 largest wildfires known to have occurred since 1920, nine burned exclusively in the Boreal White and Black Spruce (BWBS) biogeoclimatic zone and five burned primarily in the BWBS but also into the zone above it, the Spruce – Willow – Birch (SWB). These 14 fires account for 1,280,700 hectares of the estimated total of 1,556,300 hectares represented by the largest 20 wildfires for the province (or 83% of that area). The largest fire on record occurred in 1958 and covered 285,900 hectares, mostly in the BWBS zone. Other large fires, ranging in size from 35,800 to 68,700 hectares, occurred in the Montane Spruce (MS), Interior Cedar - Hemlock (ICH), Engelmann Spruce - Subalpine Fir (ESSF) and Interior Douglas-fir (IDF) biogeoclimatic zones, almost exclusively in the early 1930s.

Fire Regimes and Ecosystem Groups

Fire regimes are defined by the type, frequency, intensity and size of fires which affect particular ecosystems (Pyne *et al.* 1996). Fire regimes range from no or rare natural fires, to surface fires of varying frequencies and intensities, to crown fires of varying frequencies. Mixed fire regimes, with both surface and crown fires, occur in forests where some stands experience surface fires and others experience crown fires during the same fire event. Knowledge of the fire regime is important at both the stand and landscape levels.

Ecosystems form four broad groups with respect to the role of fire (Vogl, 1977):

1. Fire-independent ecosystems: are usually fire-free and the plant species possess no or few fire adaptations. Fire effects are dramatic, long-lasting and post-fire recovery is slow. Examples include some floodplain forests, wetlands and alpine ecosystems.
2. Fire-dependent ecosystems: fire is common and fuel conditions are conducive to fire spread. The plant species are adapted to fire and require it for their existence. Post-fire recovery is immediate and fire exclusion is unnatural. Examples include grasslands, oak savannahs, and lodgepole pine, trembling aspen and black spruce forests (Vogl, 1977).
3. Fire-initiated ecosystems: fire is infrequent and "catastrophic" as it terminates, but also initiates, long-lived plants. Initial revegetation is rapid but the post-fire recovery period can be lengthy – up to hundreds of years. These ecosystems are common in temperate regions and include the western white pine, western larch, coastal Douglas-fir, western hemlock and western redcedar types.
4. Fire-maintained ecosystems: light-intensity surface fires are frequent and crown fires are uncommon. Individual plants usually survive fires, which thin the stand, decrease fuel loads and select against fire-susceptible species, maintaining the community at an early- or mid-successional stage. The prolonged absence of fire is unnatural and results in fuel build-ups, increased stand density, forest health problems, invasion by late-successional species and greater susceptibility to crown fires (Vogl, 1977). Ecosystems primarily include the interior Douglas-fir and ponderosa pine types.

Natural Disturbance Types

While there are many subtle variations in the type, spatial distribution, temporal occurrence and effects of natural disturbance agents, British Columbia's ecosystems have been placed into five general Natural Disturbance Types (NDT) for planning and resource management purposes (Ministry of Forests and BC Environment, 1995):

NDT 1	ecosystems with rare stand-initiating events
NDT 2	ecosystems with infrequent stand-initiating events
NDT 3	ecosystems with frequent stand-initiating events
NDT 4	ecosystems with frequent stand-maintaining fires
NDT 5	alpine tundra and subalpine parkland ecosystems

Frequency varies according to the disturbance agent and geographic area, or biogeoclimatic zone. Knowledge of the effects of historic natural disturbances is used as a guide when considering biodiversity management objectives – specifically for seral stage distribution, patch size, old seral stage retention and representativeness, landscape connectivity, stand structure and species composition (Ministry of Forests and BC Environment, 1995; Ministry of Forests and Ministry of Environment, Lands and Parks, 1999).

Post-fire Succession

Post-fire vegetation succession varies with the pre-fire vegetation species and their state of development, the season of the burn, fire behaviour, fire intensity (heat output), fire severity (effects on the ecosystem), fire size, off-site vegetation, physical site characteristics and post-fire environmental conditions. There can be a wide range of fire effects in a large wildfire. Fire effects especially vary between fires in response to variations in fire size, topography, vegetative cover, soil characteristics and fire behaviour. The diversity of fire effects leads to a diversity of ecosystem responses.

In fire-initiated ecosystems, where the tree canopy can be entirely burned, vegetation recovery will depend on on-site or off-site adaptations. On-site adaptations include serotinous cones (lodgepole pine), root suckering (trembling aspen), root collar sprouting (birches), redevelopment from specialised rooting structures (rhizomatous shrubs and herbs) and seed stored in the soil which germinates following heat treatment (snowbrush and other shrub species). Off-site adaptations are exhibited by different herbs, shrubs and trees in the form of many light seeds which colonise the burned area.

Stand-maintaining fires suspend forest succession, preventing conversion to later-successional communities. The thick bark of older ponderosa pine, Douglas-fir and western larch enable them to survive surface fires. Large and open-grown ponderosa pine have their lower trunks clear of branches, thus lessening the chance that fire will move into the crowns. Most native herb and shrub species in these types are also fire-adapted by virtue of protected buds or the ability to regrow following fire.

Fire also affects soil processes, nutrient cycles, stream water chemistry, hydrological and geomorphological processes, various aspects of plant and animal habitat and air quality. Knowledge of the relationships between fire behaviour, fire effects and ecosystem response is required to predict the impacts of wildfires or when planning and executing prescribed burns.

Aboriginal Burning

Aboriginal peoples used prescribed fire to manage food and medicinal plants, wildlife habitat, and domestic range. Fire was also used to reduce fuel loadings around habitations. Burning was done at specific times of the year, under certain weather conditions and required special knowledge of fire behaviour and vegetation response.

At least 18 species of plants, including 12 fruiting shrubs and 6 plants with edible roots have been consistently identified by the First Nations peoples of BC as being purposefully encouraged by traditional burning practices. The major target plants were berry producers such as *Vaccinium* and *Rubus* species, nodding wild onion, several lilies, salal and soopolallie. Burning for berry production also took place on the west coast of Vancouver Island and on Haida Gwaii.

In some cases, individual plants such as hazelnut were burned, but primarily specific patches were treated with fire on perhaps a four- or five-year cycle. Such rotational burning kept a larger landscape area in constant production. The favourite locations for prescribed burning might have been close to a village or seasonal camp, or far enough away to require a special trip to harvest the current year's crop and carry out a prescribed burn (Gottesfeld, 1994).

A special case is the edible blue camas, whose bulbs provided a source of carbohydrates for the aboriginal peoples of southern Vancouver Island and nearby Washington state. Growing in prairies and Garry oak woodlands, this plant was harvested in the late spring and early summer and then the area was burned over later in the summer or in the early fall (Turner, 1991; Beckwith, 2002).

In general, the native peoples were adept at prescribed burning and used low intensity fires to create and maintain fine-scaled mosaics of communities of preferred plant species. In addition, their role in affecting the landscape as a result of carelessness leading to large-scale wildfires cannot be overlooked. While prescribed burning by native peoples was likely reasonably constant and sometimes quite local, the impact of non-natives in their use of fire was more abrupt and widespread.

The Settlement Era

Beginning with the settlement era of the late 1800s, exploration, industrial activity and land clearing resulted in many accidental and serious wildfires. In response to an increasingly-blackened landscape, the *Bush Fire Act* was passed by the Legislative Assembly in 1874 (SBC, 1874). This act provided for fines up to $100 or three months imprisonment for allowing unextinguished fires to escape and damage private or Crown land. However, the first Fire Wardens and fire-fighting crews were not hired until 1905 and so the law was of limited use and rarely enforced.

Controlled burning was used by settlers to clear forest land and permit agricultural development as well as to dispose of hazardous slash on logging operations, all with the encouragement of provincial government agencies. Nevertheless, escaped fires were common and between 1910 and 1916 the majority of wildfires resulted from campers, railways and land clearing operations. Two major concerns at this time were the prevention of wildfires on harvested areas regenerating naturally to new forests and the use of appropriate methods to reduce fires caused by railway and logging locomotives.

Fire Control and Fire Management

The first provincial *Forest Act*, passed in 1912, addressed fire prevention, established a fire season, required permits for the use of fire, directed that slash and other flammable debris be disposed of, and required fire patrols along railways (also subject to federal law and regulations) and at logging operations (SBC, 1912). The act also created the Forest Protection Fund, maintained by owners of timber land

and the Crown to man and equip an expanding provincial fire-fighting force and construct trails, lookouts and communication lines.

Over the ensuing decades, technological improvements were made in fire detection and suppression. More and more lookouts were built and manned; fire roads and access trails were constructed; fire pumps and hose became lighter and more effective; aircraft were used to detect fires, deliver equipment and crews and finally were employed as air tankers in a direct fire suppression role. Land-based communication lines gave way to sophisticated radio and data transmission networks. Helicopters are now used to deliver Helitack and Rapattack fire suppression crews as well as act as helitankers to carry water or foam mixtures that are dropped or off-loaded to a portable reservoir near a wildfire. Electronic and computer technology in the 1970s and 1980s brought in remote automated weather stations, lightning detection and location networks and real-time data management and decision support systems.

Fire and Resource Management

Technology allows us to choose to influence natural wildfires and employ prescribed fire, but the role that fire plays in resource management is determined by the specific objectives for particular landscapes and ecosystems. The ecological outcome of any fire can be known or estimated in advance and the fire then judged to be negative, neutral or beneficial. Fires must be evaluated in light of both long-term fire regimes and human activities.

Consideration of the environmental and social implications of a particular fire event determines the appropriate response – whether or not to suppress a wildfire or whether or not to apply prescribed fire. In most cases, protection of life and limb, property values, timber resources and transportation and utility corridors demand fire suppression actions. Resource management plans for ecological reserves and protected areas include consideration of the natural role of fire and provide details as to when and where fire, natural or prescribed, is desired.

Prescribed Burning

In contrast to controlled burning, prescribed burning is more sophisticated and defined as "the knowledgeable application of fire to a specific land area to accomplish predetermined forest management or other land use objectives" (CIFFC, 2003). As knowledge of fire behaviour and fire effects improved, along with technological innovations such as ignition systems and suppression equipment, controlled burning evolved into more sophisticated prescribed burning.

Prescribed burning has been carried out to abate the fire hazard by reducing fuels resulting from harvesting operations and to meet silvicultural objectives – prepare a seedbed, enable access by tree planters, create plantable spots, bring about tree species conversion or site sanitation against certain insects or diseases, maintain stocking control and reduce levels of competing vegetation.

Prescribed burning for wildlife habitat and domestic range improvement has been carried out to manipulate species composition (remove unwanted vegetation and encourage wanted vegetation), improve the quantity and/or quality of forage and browse, create or improve access and change vegetative cover characteristics.

Ecosystem restoration treatments may be required where decades of fire exclusion have resulted in unacceptable changes, especially in the case of fire-maintained ecosystems. Resource and fire managers must recognize the need to restore and/or sustain ecosystems, by various means, and yet fire cannot always be easily or safely reintroduced. Major challenges are the choice of appropriate treatment and the ability to treat large enough areas to effect significant ecosystem restoration at the landscape level.

Combustion

What makes a fire burn? Why does one fire barely creep along while another becomes a roaring inferno? When forest fuels burn, oxygen in the air combines chemically with woody material, pitch and other burnable elements found in the forest environment in a process known as combustion.

Combustion is a chain reaction chemically similar to photosynthesis, but in reverse. Photosynthesis requires a large amount of heat that is furnished by the sun. The combustion process releases this heat in a process sometimes called "rapid oxidation." Combustion is similar to the formation of rust on iron or the decay of dead wood in the forest, except that the process is very much speeded up.

During combustion, oxygen rapidly combines with the fuel and converts it into gases, primarily water (H_2O) and carbon dioxide (CO_2), as well as various residual by-products. The reaction produces significant thermal energy (heat) and light, and is generally self-sustaining in that no external heat source is required to maintain fuel combustion.

Fuel Chemistry

There are three phases to the combustion process: preheating, flaming combustion and glowing combustion. During preheating, the moisture in the fuel is first evaporated at temperatures > 100°C, then the cellulose is thermally broken down and those breakdown products are then volatilized (at > 200°C). This partial breakdown of cellulose molecules produces flammable hydrocarbon gases which ignite (at from 300–400°C), combining with oxygen to produce flaming combustion. The reaction for the flaming combustion of cellulose is written as:

$$C_6H_{10}O_5 + 6O_2 \overset{h}{\Rightarrow} 6CO_2 + 5H_2O + \text{Heat Energy}$$

Flaming combustion requires ignition energy, which can be represented by the simple relation (Van Wagner, 1977):

$$h = 460 + 26m$$

where: h = ignition energy in kJ/kg, and
m = moisture content (%) of the fuel expressed as a percentage of its oven dry weight

Ignition energy requirements increase sharply with increasing fuel moisture content. The moisture content of extinction – the maximum moisture content at which a fire will be self-sustaining and still spread – is hard to specify. Fire spreads poorly in surface litter with moisture contents greater than 30%, while conifer foliage can support fast-spreading crown fires at moisture contents of 100% or more.

After flaming combustion has ignited and burned off most of the volatile elements, the remaining carbon may burn as a solid by a surface oxidation process called glowing combustion. Flaming and glowing combustion are not discrete temporal events due to the complex mixture of wildland fuel sizes, moisture contents and arrangements but rather occur at the same time within an individual fire.

Heat Transfer

Heat transfer is the process by which heat is imparted from one body or object to another. Heat energy is transferred from burning to unburned fuels by conduction, convection, radiation and solid mass or ember transport (spotting) although conduction plays a relatively minor role in the spread of wildland fires.

Convective heat transfer through the movement of hot air usually occurs upwards in the absence of significant winds or slope (CIFFC, 2003). As a result of pressure gradients, the heated and therefore expanded parcel of air becomes buoyant and displaces, transporting heat by convection, in addition to some conduction. Such heat-induced motion in initially static fluids is called "free convection."

When the air mass is already in motion, conducted heat will be transported away – chiefly by fluid convection. These cases, known as "forced convection," require a pressure gradient to drive the motion, as opposed to the gravity gradient that induces motion through buoyancy.

Radiation transfers heat in straight lines from warm surfaces to cooler surroundings (CIFFC, 2003). All materials radiate thermal energy (as a function of their temperature), which is carried by photons of light in the infrared and visible portions of the spectrum. When temperatures are uniform, the radiative flux between objects is in equilibrium and no net thermal energy is exchanged. The balance is upset when temperatures are not uniform, and thermal energy is transported from surfaces of higher to surfaces of lower temperature.

Conduction is the transfer of heat through solid matter (CIFFC, 2003). Regions with greater molecular kinetic energy pass their thermal energy to regions with less molecular kinetic energy through direct molecular collisions. Grasses, herbaceous plants and wood are poor conductors of heat and therefore this heat transfer mechanism is of nominal importance to the propagation of wildland fire.

Fire Spread

Three elements must be present and in a satisfactory combination before ignition and combustion can occur and continue. For the sake of simplicity we combine these elements into the fire triangle:

1. there must be fuel to burn,
2. there must be oxygen, and
3. there must be heat (ignition temperature) to start and maintain the combustion process. The sun is the primary source of heat in our environment and heat from the sun drives our weather.

When any one of these three factors is removed, flame production is impossible or ceases.

The three distinct yet simultaneous phases of preheating, flaming combustion and glowing combustion can be plainly seen in a spreading fire (Figure 1).

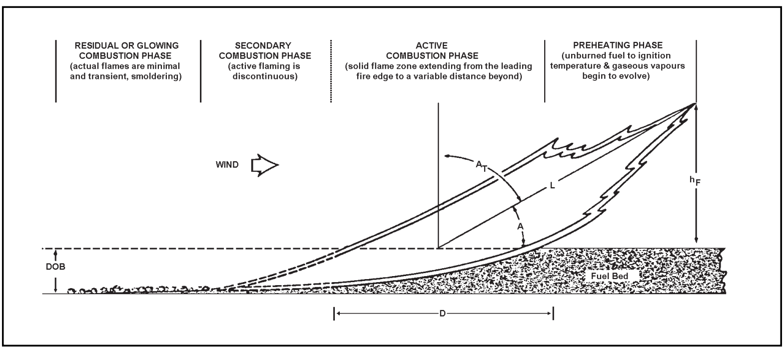

Figure 1: Cross-section of a spreading fire, where h_F = flame height, L = flame length, A = flame angle, A_T = flame tilt angle, D = flame depth and DOB = depth of burn (from Alexander, 1982).

In the initial stages of fire development, under calm conditions on level terrain, the flames draw into the centre of the flaming zone (Figure 2). After 10–15 minutes the fire develops a doughnut shape, with the flames leaning inwards. Under windy conditions, flames can lean with the wind shortly after ignition. They will also develop a lean upslope on sloping ground. After the centre area begins to burn-out the rear of the fire will spread slowly against the wind as a backing fire with low flame heights, while the front or head of the fire with the highest flame heights will run upslope or with the wind. The portion of the fire that spreads at roughly right angles to the prevailing wind or slope is known as a flank fire.

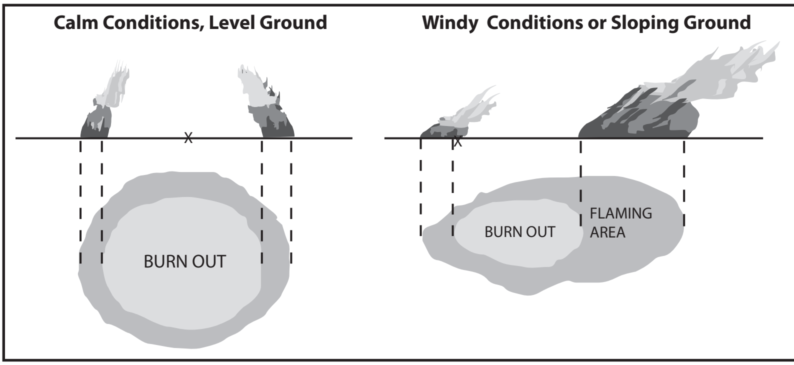

Figure 2: Initial fire spread (after Luke and McArthur, 1978).

Fire Acceleration

Fires can originate as a point or a line source. Fires originating from a point source (such as a match, campfire or lightning strike) accelerate through time until they reach a pseudo steady-state rate of spread or equilibrium rate of spread. In reality the acceleration pattern may be stepped, and this can be attributed to the progressive consumption of various fuel layers, the formation of a convection column and ultimately solid mass transport or spotting (Figure 3). Nonetheless, a more simple mathematical relationship is assumed to calculate a theoretical rate of spread with time since ignition (Figure 4). The time to reach an equilibrium rate of spread is dependent on fuel type, but in timbered fuels it takes about 30 minutes for a fire to reach its equilibrium rate of spread.

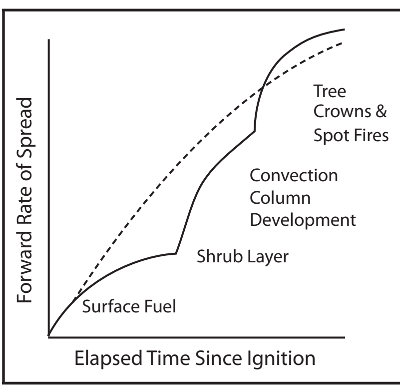

Figure 3:
Acceleration pattern of forest fires.

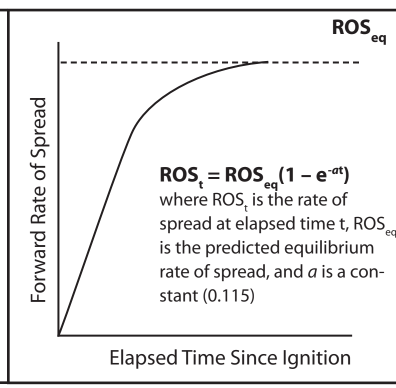

Figure 4:
Theoretical rates of spread with time.

With a reasonably constant time to reach equilibrium, it follows that the rate of acceleration will vary greatly depending on the equilibrium rate of spread, which in turn is a function of a number of factors in the fire environment such as fuel moisture, terrain and wind exposure. Fire shape and size characteristics, such as total length, maximum breadth and length-to-breadth ratio also vary with time since ignition. It is important to realize that the application of equilibrium rate of spread models during the incipient stages of a fire will over-predict spread rates, area burned and perimeter lengths.

Fires originating from line source ignitions, such as when an established flank fire becomes a head fire in response to a wind shift, are considered to reach an equilibrium rate of spread almost immediately. Therefore, a line source fire will travel further than a point source fire after the same elapsed time (Figure 5).

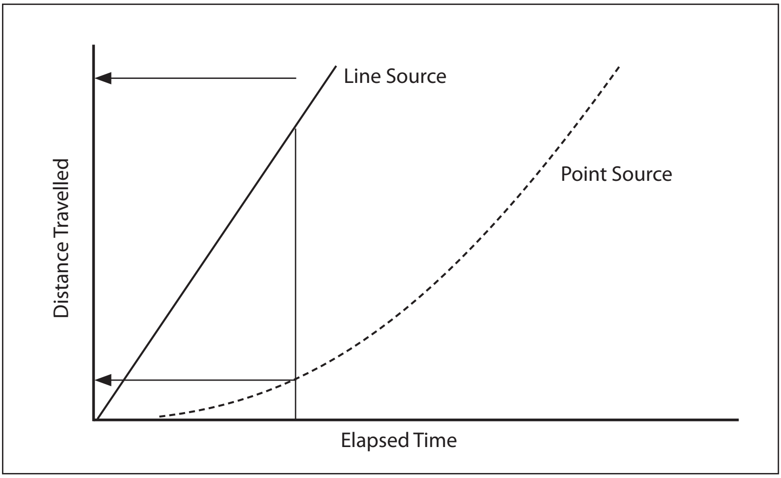

Figure 5: Point source vs. line source fire spread.

Fire Growth

Although a fire originating as a point source assumes a circular shape immediately after ignition, under the influence of a wind or slope it becomes roughly elliptical in shape (Figure 6). This feature allows the determination of fire perimeter length and fire area from simple mathematical formulas (Van Wagner, 1969).

The area of a simple ellipse is represented by πab, while the perimeter or circumference is represented by $2\pi \sqrt{(a^2 + b^2) / 2}$

Several assumptions are made in the application of simple mathematical models to predict fire growth. For example, the following apply for a wind-driven fire:

- the fire was lit at a single point source,
- the linear rate of spread at each point on the fire remains constant,
- the wind speed and direction are constant,
- the terrain is flat or its influence is negligible,
- the fuels are continuous and homogeneous, and
- man-made or natural barriers do not impede fire growth.

The relationship between the length and breadth of the ellipse is a function of wind or slope (Figure 7). The stronger the wind or slope, the greater the length-to-breadth (L/B) ratio. To arrive at an L/B ratio for slope-driven fires, slope is converted into a wind speed equivalent. In the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group, 1992), an empirical relationship was developed to describe how L/B ratios of fires in standing timber fuel types vary with wind (Alexander, 1985). The L/B relationship for grass fuel types is based on the analysis of experimental and wildfires in Australian grasslands (Cheney, 1981).

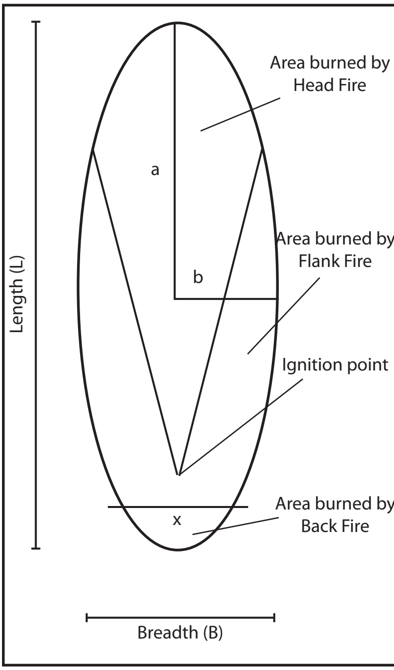

Figure 6:
Simple elliptical fire growth model.

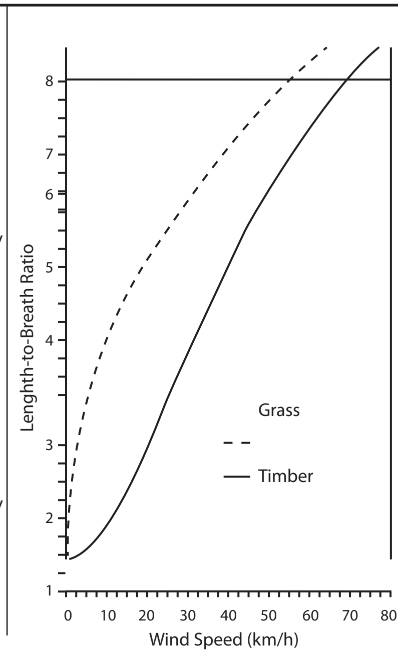

Figure 7:
L/B ratio vs. wind speed.

Frontal Fire Intensity

The active front of a forest fire has three basic characteristics: 1) it spreads, 2) it consumes fuel and 3) it produces heat energy in a visible flaming combustion reaction. Fire intensity is the rate of heat energy release per unit time per unit of fire front (Byram, 1959). Intensity is calculated accordingly:

$$I = Hwr$$

where: I = fire intensity (kW/m),
H = fuel low heat of combustion (kJ/kg),
w = weight of fuel consumed per unit area (kg/m^2) in the active flaming zone, and
r = linear rate of fire spread (m/s)

The amount of heat released per unit mass is called the heat of combustion. The high heat of combustion is the maximum heat release of dry fuel completely combusted (both flaming and glowing) to water and CO_2. The low heat of combustion (also known as the heat yield) adjusts the high heat of combustion downward to account for heat losses resulting from incomplete combustion and the presence of fuel moisture. The low heat of combustion is associated with the volatiles given off when the fuel is heated. For forest fuels, the low heat of combustion varies so little that it is usually thought of as a constant value. In Canada, 18,000 kJ/kg is commonly assumed.

If 18,000 kJ/kg is used as a standard value for the heat of combustion (*H*), a value of 300 allows us to use m/min rather than m/sec as the spread rate unit (since 18,000/60 = 300):

$$I\,(\text{kW/m}) = 300\; w(\text{kg/m}^2)\; r\,(\text{m/min})$$

All fuel consumption is assumed to occur in the active flaming zone rather than via smouldering combustion.

Fire effects can be related to fire intensity. For example the height of lethal crown scorch (h_s), which is the browning of foliage in a tree crown caused by the heat rising above a surface fire (as a result of convection) can be related to Byram's fire intensity:

$$h_s = 0.1483\,(I)^{2/3}$$

where: h_s = lethal scorch height (m), and
I = fire intensity (kW/m)

Fire intensity is directly related to many aspects of the flame geometry of the fire front (Alexander, 1982). For instance, flame length (refer back to Figure 1) has been empirically related to fire intensity (Figure 8):

$$I = 259.833(L)^{2.174}$$

where: I = fire intensity (kW/m), and
L = flame length (m)

However, the following rule of thumb is regarded as adequate for field use:

$$I = 300(L)^2$$

Fire intensity influences the distance spot fires will be thrown and whether or not existing or prepared barriers to fire spread will be breached. Thus, fire intensity is one of the major determinants associated with the likelihood of controlling or containing a free-burning wildland fire (Hirsch *et al.* 1998) and in turn the strategy and tactics to be adopted for safe and effective fire suppression.

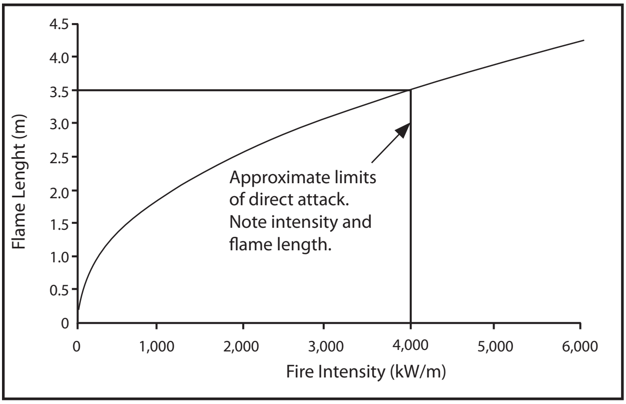

Figure 8: Flame length vs. fire intensity.

Crown Fires

The transition from a two-dimensional to a three-dimensional fire is achieved through crowning. There are three classes of crown fires according to Van Wagner (1977) and CIFFC (2003):

1. intermittent or passive crown fires are those in which trees torch sporadically as individuals, reinforcing the spread rate, but are not basically different from surface fires.
2. active crown fires are those in which a solid flame develops in the crowns, but the surface and crown phases advance as a linked unit, dependent on each other.
3. independent crown fires advance in the crowns alone.

Passive crown fires are common in open-canopied forests. Active crown fires are common in closed-canopied forests, where the fire crowns after a substantial surface fire develops and then they spread as a linked unit. A strong wind is first required to intensify the surface fire until crowning occurs – otherwise the fire will fall back to the surface if the wind subsides. Independent crown fires are rare and can only exist for short periods of time during extreme wind events and/or on very steep slopes.

The class of crown fire to be expected in a conifer stand on any given day depends on three simple properties of the crown fuel layer and two basic fire behaviour characteristics:

- initial surface fire intensity,
- foliar moisture content,
- live crown base height,
- crown bulk density, and
- rate of fire spread after crowning

Van Wagner (1977) theorised that vertical fire spread will occur in coniferous stands when the surface fire intensity (I_s) attains or exceeds a certain critical surface intensity (I_o) value (i.e. $I_s \geq I_o$):

$$I_o = [0.01 \times z \times h]^{1.5}$$

where: I_o = critical surface intensity for crown combustion (kW/m),
z = height to live crown base (m), and
h = ignition energy (kJ/kg) = 460 + 26m, where m = moisture content (%)

The critical surface fire intensity can also be derived from look-up tables. Once the critical surface fire intensity has been calculated, it can be compared with a predicted surface fire intensity. If the predicted surface fire intensity is the lesser ($I_s < I_o$) the fire is classified as a surface fire; if the predicted surface fire intensity is the greater ($I_s \geq I_o$), then crowning is assumed to occur.

Wildfires and suppression operations, particularly in the wildland-urban interface will generate great public impact, disruption and concern. Fire behaviour analyses are fundamental to safe and effective fire suppression efforts. It is equally important to identify situations that are not likely to experience suppression success. Through advanced notification of wildfire and suppression realities, much can be done to prepare for and mitigate some of the negative reactions that accompany fire suppression operations in settled areas.

Fire Control Strategies

With a continuous supply of heat (furnished by the combustion process itself), the ignition of additional fuel will continue as long as enough oxygen is present. Therefore, when you tackle a going fire, you should consider how best to use personnel and equipment to remove one or all of the sides of the fire triangle. Remove any one of the three sides or elements and the fire will cease to burn. Weaken any one, and the fire will weaken. Increase any one or more of the elements, and the fire will increase in intensity. Armed with this knowledge the fire fighter or prescribed burner can do much to manage a fire.

Fire Control Tactics

Good fire-fighting is therefore often a skilful combination of removing fuel, heat and oxygen. Fire control is achieved by breaking the fire triangle, in one or more ways.

Reducing heat

This may be accomplished by cooling fuels with water, fire-fighting foam, or dirt or scattering the available fuels to reduce the effects of radiant heat. Water or dirt should be applied directly to fuels in order to reduce fuel temperature. As flames are actually the burning gases liberated by heated fuels, cooler fuels release less gases and therefore have a lower probability of ignition and combustion.

Reducing air and oxygen

Water, foam, dirt and fire retardants will reduce the supply of oxygen for the combustion process. Artificial fog can be created with a special hose nozzle to smother the flaming gases by occupying the air space with millions of fine particles of water. This can also be accomplished with chemical retardants dropped from fixed-wing aircraft or helicopters or applied from the ground.

Fires burning in forest fuels are difficult to completely smother with dirt, even when it's damp, because of the porous nature of most soils. Soil can be applied to slow down a fire by reducing its intensity. Plain water is more effective but the excess quickly runs off.

Foams and fire retardants are most effective because they are long-lasting – the former is applied to the flames as a suppressant, the latter is applied adjacent to the flames to coat the unburned fuels and act as a fire barrier.

Fire-fighting foam reduces the supply of oxygen more effectively than does plain water by completely coating the fuel. The majority stays on the surface and evaporates very slowly, protecting the fuel from heat and reducing the supply of oxygen. As the surface tension of water is reduced, more water is absorbed into the fuel. This additional fuel moisture absorbs heat as it is changed to steam and driven off. Consequently, more heat is required to bring the fuel to ignition temperature and therefore the fire's effectiveness is reduced. Foam can also be used very effectively in prescribed burning operations.

Removing fuel

Removing fuel is the most common method of attacking wildfires. This method does not extinguish the fire, which continues to burn until the available fuel is consumed. Rather, the physical removal of fuel from the path of a fire prevents it from spreading past that fireline. A slow-moving ground or surface fire may be checked by a fireline constructed down to mineral soil. Several firelines and/or "burning out" of the remaining fuel between a fireline and a hot, fast-moving surface and/or crown fire may be required in order to bring it under control. By burning the available fuel in advance of the fire front, the fuel is effectively removed and therefore unavailable to the oncoming fire.

Chemical fire retardants (applied from the ground or by air) "remove" the fuel by coating it with a barrier that protects the fuel from preheating and cuts off the supply of oxygen. The available fuel thus becomes unavailable fuel, incapable of burning. Retardants are long-lasting, continuing to be effective after the water that was used as a carrier has evaporated.

The Fire Environment

Placing fire in a broader context, the fire environment is defined as "the surrounding conditions, influences and modifying forces of topography, fuel and weather that determine fire behaviour." Fire behaviour is "the manner in which fuels ignite, flame develops, and fire spreads as determined by the interaction of fuels, weather and topography" (CIFFC, 2003). The primary factors that influence fire behaviour are known as the fire behaviour triangle: fuel, weather and topography. How a given fire behaves is determined by the state of these three factors (Countryman, 1972). A change in any one will change the characteristics of the fire.

Fuel

Fuel properties such as type, arrangement, quantity or load, size distribution, continuity and moisture content are important for assessing potential fire behaviour. Forest fuels are either live or dead and with wildland fire we are primarily concerned with the dead fuels on the forest floor. Fuels are classified as aerial, surface or ground

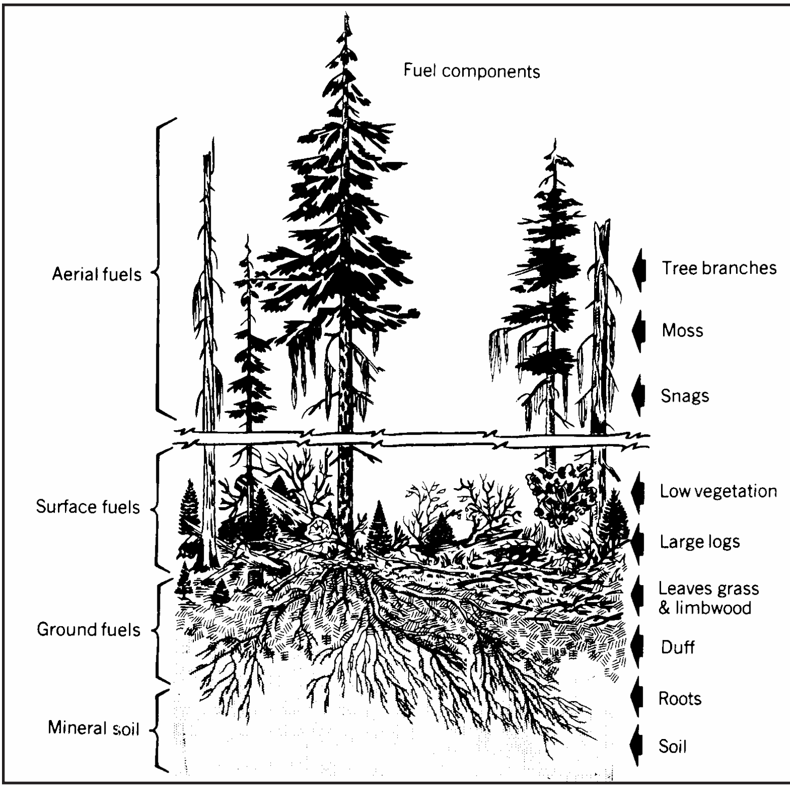

Figure 9:
Components of a forest fuel complex (from Pyne *et al.* 1996).

fuels (see Figure 9).

A fuel complex or type is an identifiable association of fuel elements of distinctive species, form, size, arrangement and continuity that will exhibit characteristic fire behaviour under defined burning conditions. Fuel continuity describes the distribution of fuels. Uniform fuels have a contiguous distribution, whereas patchy fuels are distributed unevenly with distinct inclusions of fuels of a much lower flammability. Continuity is an important factor in fire behaviour since the distribution of fuels may enhance or limit fire spread. If fuels are uniformly distributed throughout an area, there is a high potential for a complete, rapid burn and the fire may be difficult to control.

Fuel load is the oven dry weight of combustible materials per unit area, and is usually expressed in kilograms per square metre (kg/m^2) or tonnes per hectare (t/ha). As the amount of fuel available for combustion increases, the heat produced by the fire increases. When both small and large fuel size classes are present, small fuels act as kindling for larger fuels.

Fire burns rapidly in loosely compacted fuels because individual fuel particles are readily exposed to oxygen. Compacted fuels such as piled logging debris and duff burn more slowly because of the lack of space for oxygen between fuel particles.

Moisture content is a critical factor in determining the flammability of a given fuel complex. When fuels are green or moist, fire will spread slowly if at all. When grasses are fully cured and dry, fire will spread at an extremely rapid rate. Dead fuels gain and lose moisture as they attempt to come into balance with the atmosphere that surrounds them, and the rate at which they do so depends on particle size, porosity and amount of exposed surface area.

Species, canopy cover, ecological moisture regime and exposure all influence the moisture characteristics of a given fuel complex. In North America at least, live deciduous leaves are less flammable than live conifer needles because of differences in the moisture content, surface area-to-volume ratio and chemical composition. The flammability of mixedwood forests varies with the proportion of conifer versus deciduous species, and whether or not the deciduous overstorey, grasses, herbaceous plants and shrubs in the understorey have flushed in the spring. Surface fuels beneath dense stands may dry out slowly due to less exposure to solar radiation and wind, but will also receive less precipitation than more open stands due to canopy interception.

Weather

At a more specific level than the large-scale general circulation of high and low pressure systems and the many complexities of regional weather, fire weather – the components of weather that determine fire incidence and behaviour – includes relative humidity, temperature, wind speed and direction and precipitation. Hourly, daily, weekly, monthly and yearly variations in weather conditions all exert some influence on how, when and where fires will start; how they will behave once ignited; and how difficult they will be to control.

Weather is of special importance because it may change quickly and hence fire behaviour characteristics may also change rapidly as a result. At low relative humidities, fuels dry out sooner and at higher temperatures less energy from a fire will be required to raise unburned fuels to their ignition points. Temperature and relative humidity are inversely related such that at higher temperatures, relative humidities are lower.

Wind speed and direction exert strong influences on fire behaviour, along with fuel moisture and slope. Wind supplies oxygen to the combustion process, physically moves heat and fire and increases evaporation rates. If fuel and topography remain constant, wind is the prime determinant of the direction of fire spread, rate of spread, fire size and fire shape. Large fires often create their own very strong local winds, which add more complexity to predicting fire behaviour.

General winds result from global-scale variations in temperature and air pressure, while local winds are a product of terrain and local differences in heating and cooling. In mountainous terrain, winds flow upslope during the day in response to heating and downslope at night in response to cooling. The speed and daily regime of these winds varies with aspect. Differential heating and cooling of the ocean and adjacent land masses give rise to sea breezes blowing onshore during the day and land breezes blowing offshore during the night. After the passage of a cold front, local winds will change direction and may increase in speed. These relationships can aid or hinder wildfire control and prescribed burning operations.

In addition to the effects of relative humidity and temperature, the moisture content of fuels is determined by precipitation, primarily as rainfall and dew. The timing, duration and amount of precipitation received during the fire season helps to determine fire incidence and on a shorter time frame influences fire behaviour and spread.

Historically, the largest forest fires in North America occurred under extreme burning conditions when extended fire season drought created very dry fuels and fires accompanied by high temperatures, low relative humidities and/or strong winds lead to rapid rates of spread. Fires have also occurred outside the usual fire season, notably after unusual winter drought and early spring drying. Some fires burning under extreme conditions do not moderate their behaviour at night, thus adding to fire control difficulties. Large wildfires burning under extreme conditions are virtually impossible to control, in which case specific resources or values at risk are defended until weather conditions change and rain and/or snow events extinguish the entire wildfire.

Topography

Elevation, slope, aspect and terrain are highly variable over the landscape, changing especially quickly in mountainous areas. Elevation influences climatic regimes and therefore the total annual precipitation, the proportion of precipitation falling as snow, snow melt rates, and vegetation greenup and curing dates. Elevation is directly linked to the fuel complex and length of the fire season.

Slope aspect and angle are large determinants of the amount of solar energy received by a site and, in combination with other factors, influence the vegetation type which is present, therefore the fuel complex, and ultimately the fire regime. For example, a south aspect can be covered with an open grass – shrub mixture while the north aspect at the same elevation of the same hill or mountain may support a closed coniferous forest. Each fuel complex has different ignition probabilities and fire behaviour potentials.

Because of the direction of travel of the sun through the sky, East-facing slopes heat up first, reaching their highest temperature before all other aspects. South-facing slopes reach their maximum temperature about two hours later and it can be higher than that experienced on an East-facing slope. West-facing slopes reach their maximum temperature still later, and it can be higher than those of both east- and south-facing slopes. North-facing slopes have a lower range of temperatures through the day and the peak daily temperature is lower than those for all other aspects. The specifics of these relationships vary with cloud cover, slope, time of day, time of year and latitude (Countryman, 1966; Pyne *et al.* 1996).

Because local air temperatures and relative humidities are affected by these aspect relationships, variations in fuel temperature and moisture content result. Slope position also affects the daily temperature and humidity regimes, thus adding another determinant of fuel condition and availability. As a wildfire burns through different elevations and different aspects, its behaviour varies as it encounters different fuel complexes in a variety of conditions. The behaviour of a fire at a particular location will change as solar insolation, air temperatures and relative humidities change through the day.

Slope angle affects the ability of a fire to heat adjacent unburned fuels. Fires spreading upslope are more effective at heating by radiation and convection and behave as if they are running with the wind. Fires backing down a slope behave as if they are burning into the wind, although burning woody debris rolling downslope can encourage more rapid fire spread at lower elevations.

Larger terrain features also affect fire behaviour and spread. Weather conditions may be more variable in mountainous terrain, especially with respect to wind speed and direction. Fires on one side of a steep ravine direct radiative heat to the opposite side and bring those fuels to ignition sooner. In a box canyon, or chimney, both radiative and upslope heating, aided by unstable air, can lead to extreme fire behaviour. On the other hand, terrain features such as bare rock, talus slopes, lakes and rivers, riparian areas, roads and trails can act as a barrier to fire spread and serve to moderate fire behaviour.

The Canadian Forest Fire Danger Rating System[1]

Forest fire danger rating research in Canada was initiated by the federal government in 1925. Five different fire danger rating systems have been developed since that time, each with increasing applicability across Canada. The approach built on previous danger rating systems and used field experiments and extensive empirical analysis.

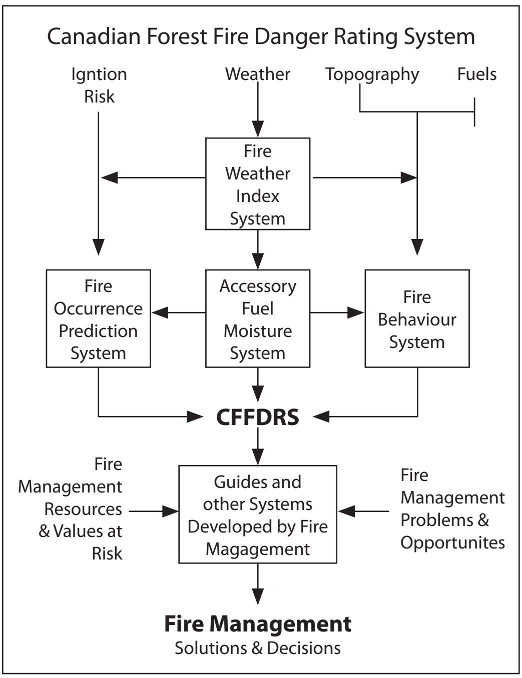

Figure 10:
Simplified CFFDRS structure diagram illustrating the linkage to fire management actions.

The current system, the Canadian Forest Fire Danger Rating System (CFFDRS), consists of two major subsystems (Figure 10). The Canadian Forest Fire Weather Index (FWI) System provides numerical ratings of relative fire potential for a standard fuel type on level terrain. The Canadian Forest Fire Behavior System accounts for variability in fire behaviour amongst fuel types for a given slope steepness based on certain FWI System components.

The Fire Weather Index System

The FWI System assesses relative fire potential based solely on weather observations. The six components individually and collectively account

[1] Much of the text in this section has been adapted from Van Nest and Alexander (1999) with kind permission of the authors.

for the effects of fuel moisture and wind on ignition potential and probable fire behaviour in the form of relative numerical ratings (Figure 11). Three fuel moisture codes reflect the fuel moisture content of fine surface litter (Fine Fuel Moisture Code, FFMC); loosely compacted duff of moderate depth (Duff Moisture Code, DMC); and deep compact organic matter (Drought Code, DC), respectively. The codes are dynamic bookkeeping systems that account for the effects of each day's precipitation and drying.

The fuel moisture codes plus wind are linked in pairs to form two intermediate and one final index of fire behaviour. The Initial Spread Index (ISI) combines the effects of wind and fine fuel moisture content (FFMC). It represents a numerical

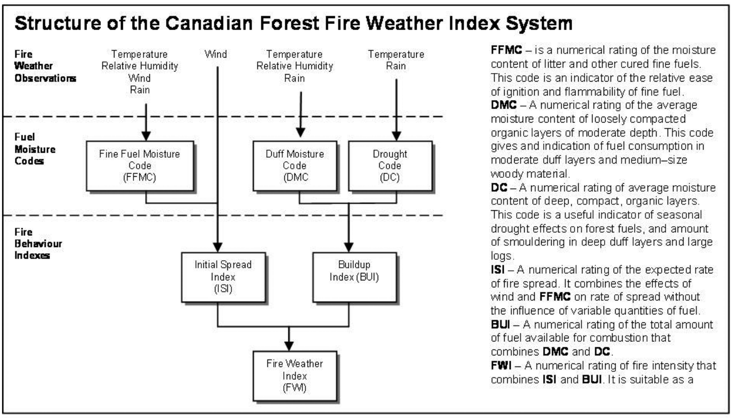

Figure 11:
Structure of the Canadian Forest Fire Weather Index System and component definitions.

rating of fire spread rate, without the influence of variable fuel quantity. The Buildup Index (BUI, based on the DMC and DC) represents a measure of the total fuel available for combustion.

The Fire Weather Index (FWI) component itself combines the ISI and BUI to indicate the potential intensity of a fire on level terrain in a stand of mature pine. Because jack pine and lodgepole pine forests form a more or less continuous band across Canada, the concept of a standardised fuel type is reasonable.

FWI System components depend solely on daily measurements of dry-bulb temperature, relative humidity, a 10-metre height open wind speed and 24-hour accumulated precipitation, recorded at noon local standard time. Because calculation of the components depends solely on weather readings, they can be calculated from forecast weather to yield a fire danger forecast.

The FWI itself is a good indicator of several aspects of fire activity and is best used as a measure of general fire danger for administrative purposes. However, it is impossible to communicate a complete picture of daily fire potential in a single number. The subsidiary components also need to be examined for proper interpretation of past and current weather effects on fuel flammability.

Each component of the FWI System conveys direct information about certain aspects of wildland fire potential. For example, the FFMC is a useful indicator of human-caused ignition probability, as is the DMC for lightning-caused ignitions. The DC and the BUI are excellent indicators of smouldering combustion or fire persistence in deep compact organic layers and hence of mop-up difficulty.

The Fire Behaviour Prediction System

The relative numerical values of the FWI System components have different meanings in different fuel types because the system was developed to rate relative fire potential in a generalised standard fuel type. The FBP System (Figure 12) addresses the variation in fire behaviour with fuel type, in quantitative terms.

The technical derivation of the FBP System rests on a sound scientific basis developed from real-world observation and measurement of numerous experimental

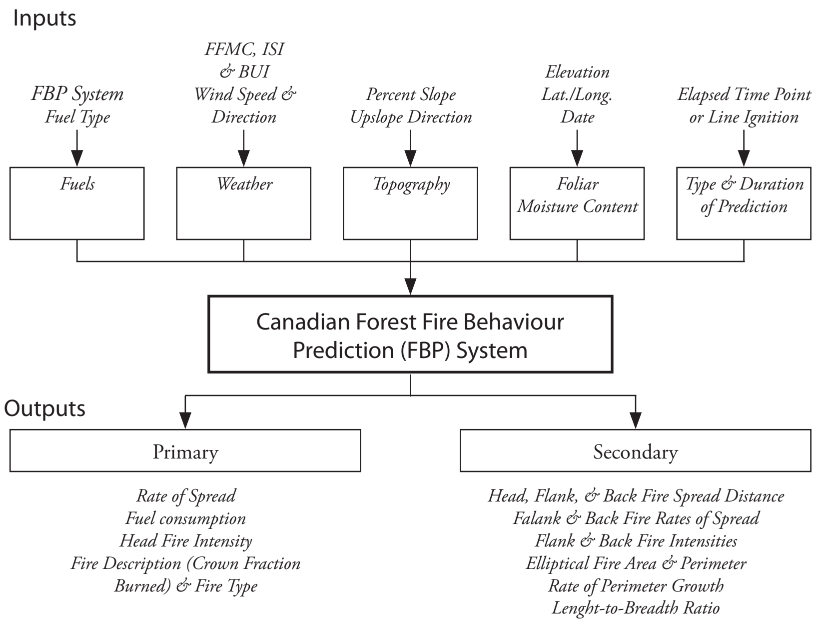

Figure 12:
Structure of the Canadian Forest Fire Behaviour Prediction System.

fires, coupled with many well-documented wildfires and operational prescribed fires, correlated against the weather-based fire danger indices of the FWI System or weather parameters for discrete fuel types. The FBP System is unique in that it incorporates the most extensive crown fire data set available anywhere.

The FBP System allows the user to predict the rate of spread (m/min), fuel consumption (kg/m^2) and intensity (kW/m) at the head, back or flanks of fires that are still accelerating or which have reached a steady-state condition with their environment. These characteristics are determined by the prevailing fire weather severity (based on wind velocity and certain FWI System components), fuel type, slope steepness, geographical location, elevation and calendar date. A general description of the type of fire is also given (for instance, surface fire, intermittent crowning or continuous crowning). A simple elliptical fire growth model is employed in estimating the size and shape of fires originating from a single ignition source as opposed to an established line of fire.

The FBP System's operation is based on a small number of readily available inputs. At present, 16 major Canadian benchmark fuel types are recognised in the system, a reflection of the empirical fire behaviour data available in Canada (Table 1).

Table 1: List of Canadian Forest Fire Behaviour Prediction System fuel types.

Group/Identifier	Descriptive name
Coniferous	
C-1	Spruce-lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6	Conifer plantation
C-7	Ponderosa pine/Douglas-fir
Deciduous	
D-1	Leafless aspen
Mixedwood	
M-1	Boreal mixedwood-leafless
M-2	Boreal mixedwood-green
M-3	Dead balsam fir mixedwood-leafless
M-4	Dead balsam fir mixedwood-green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce/balsam slash
S-3	Coastal cedar/hemlock/Douglas-fir slash
Open	
O-1	Grass

Incorporation of the best available information on forest fire behaviour in Canada into the FBP System gives fire managers the ability to predict certain fire behaviour characteristics with reasonable assurance, for a wide range of burning conditions.

For field use in predicting fire behaviour, the FBP System is available as tables or a computer program. The table format (Taylor *et al.* 1997) provides a simplified method for assessing wildland fire behaviour potential and making first approximations of FBP System outputs. Quantitative estimates of head fire spread rate; fire intensity; type of fire; and elliptical fire area, perimeter, and perimeter growth rate are provided for sixteen discrete fuel types within five broad groupings (coniferous, deciduous and mixedwood forests; logging slash; and grass).

Computer-based programs which provide all the outputs available from the FBP System range from FBP calculators such as the RemSoft DOS-based FBP93, Windows based FBP97 and BEHAVE programs to more sophisticated systems linked to GIS systems. The choice of computer program depends on the fire prediction objectives, computing capability and ability to provide sufficient data to run the computer application.

Regardless of the application, operational experience has shown that the underlying FBP system will provide reasonable predictions provided that the user understands the assumptions associated with the FBP System and that reasonably reliable data are used as input for the fire behaviour evaluation process. As with all prediction systems, the FBP System is intended to assist in decision-making, and is not a substitute for experience, sound judgement or observation of actual fire behaviour.

Applications

The CFFDRS remains one of the few nationally implemented fire danger rating systems in the world. Daily calculations of system components are made from data recorded at more than one thousand weather stations across Canada. Some current uses of the danger rating system include:

- fire behaviour training,
- prevention planning (e.g. informing the public of impending fire danger, regulating access and risk associated with public and industrial forest use),
- preparedness planning (level of readiness and pre-positioning of suppression resources),
- detection planning (e.g. lookout manning and aircraft patrol routing),
- initial attack dispatching,
- suppression tactics and strategies on active wildfires,
- escaped fire situation analysis, and
- prescribed fire planning and execution.

The CFFDRS is also being used increasingly by other wildland fire researchers and environmental scientists for applications ranging from fire suppression effectiveness and fire growth modelling to analyses of fire regimes and potential impacts of climate change.

Decision Support Systems

Fire management information systems exploit advances in computerized information handling, automatic remote collection and transmission of fire weather data, and automatic lightning detection and location networks. The value of such technologies depends, in part, on the CFFDRS to integrate the information and provide fire managers with near-real-time fire occurrence and behaviour prediction capability.

Conceptually, the CFFDRS deals with the prediction of fire potential from point-source weather measurement (i.e. a single fire weather network station). The system deals primarily with day-to-day variations in the weather, but will accommodate variations through the day as well. The system does not account for spatial variation in weather elements between points of measurement; such interpolation must be handled by models and guidelines external to the CFFDRS.

In operational practice, fire weather and fire danger forecasting procedures have been devised to integrate point-source measurement of the system's components over time and space. Spatial variation in fuels and terrain is a fire management information problem not easily handled by a fire danger rating system unless it can be linked to a computer-based geographic information system which stores, updates and displays land base information in ways directly usable by the fire manager. Geographic information systems for fire management are in use in nearly all regions of Canada. Further information on the CFFDRS is available on the Internet at:

http://cwfis.cfs.nrcan.gc.ca/

Fire Growth

Forest fire spread is not a rectilinear phenomenon; rather a fire expands in all directions, but not necessarily at the same rate. Suppression strategies must consider the rate of advance of a fire in all directions, as well as the intensity at various locations on the front.

Estimates of the perimeter length of a fire are vital for planning and assessing containment objectives. Estimates of the perimeter length of a fire at regular time intervals are used in conjunction with the size of fire fighting resources, and fireline construction rates, to determine if containment objectives can be attained with the available suppression resources.

Fire appreciation must consider priorities for the protection of life, community, commercial and environmental values. To this end, the estimated position of a fire front at various time intervals is drawn or plotted on a map, using procedures to convert spread rates into travel distances at a given map scale.

If fuel, weather and terrain conditions are continuous and homogeneous, fire mapping is a reasonably straightforward exercise using the CFFDRS. This situation occurs rarely, if ever, and therefore projecting fire growth manually is a complicated and time-consuming process. Weather forecasts are amended or do not reflect the actual situation in the field, and projections must be revised. A fire that burns for a number of days is apt to undergo considerable changes in wind velocity and other weather conditions, travels through a variety of topographic and fuel conditions, and encounters a number of natural and constructed barriers (Alexander, 1985).

Fire Modelling

A computer-assisted model, or simulation, is used to translate fire growth under homogeneous conditions into fire growth given varying conditions of fuel and terrain, under weather that varies over both space and time. The output from computer-assisted fire growth models can be applied to optimise the deployment of suppression resources; help allocate initial attack priorities given multiple ignitions; support control strategies and fireline techniques; facilitate briefing the media and the general public; or improve prescribed burn planning (Beck, 1988; Andrews, 1989).

Most of the systems developed to predict and map fire growth are largely academic exercises of event reconstruction. Few have been used operationally during an emergency situation. Canada's operational fire growth model is known as Prometheus (Tymstra, 2002) (www.firegrowthmodel.com) and fire behaviour analysts in the United States use FARSITE (Finney, 2004) (http://farsite.org/). These are fairly complicated systems that require GIS support and their outputs are unlikely to be interpreted correctly without specialised training in fire behaviour prediction and operational experience in fire management.

Even with a comprehensive fire behaviour prediction system and valid models to predict fire growth, fire management agencies across Canada are just preparing to use these systems operationally. Most fire management organisations do not have ready access to the geographic information that is required to predict fire growth. Although terrain information is readily available, fire growth models require details on fuels (Hawkes *et al.* 1995) and weather, which are not obtained easily from typical forest inventories or existing fire weather systems. Detailed spatial and temporal data, particularly for wind speed and direction, must be generated from mesoscale weather models and applied to forecast fire growth if credible results are to be expected, especially in complex terrain.

Smoke Production

Smoke is a by-product of incomplete or inefficient combustion. The only way to eliminate smoke is quick and complete fire extinguishment, which is not always possible. While wildfire smoke cannot be eliminated, its production and dispersal can be predicted reasonably well.

The amount of smoke produced by a given fire is a function of the volume of available fuel and the efficiency of the combustion process. While a conflagration level wildfire produces large volumes of smoke as a result of the area and amount of fuel being consumed, flaming combustion is still more efficient than smouldering combustion. As such, the factors influencing fire intensity and fuel consumption also influence smoke production. These include the time of year, time of day, the nature of the fuel complex, fuel moisture status, relative humidity, wind, slope and aspect.

Smoke Dispersion

Accurate prediction of the when, where and extent of wildfire smoke permits fire managers to be proactive and furthers fire fighter confidence and public credibility in the fire management organization. The transfer of pollutants through the atmosphere depends almost entirely on the fire environment and concentrations decrease either by vertical removal processes (settling, deposition and scavenging) or dispersion. In the absence of precipitation, the influence of vertical processes is assumed to be negligible.

Pollutant and smoke concentrations are proportional to the product of the depth of the turbulently-mixed layer and the speed of the wind within that layer:

$$V\ (m^2/s) = \text{wind speed}\ (m/s) \times \text{mixing height}\ (m)$$

Where V, the product of the wind speed (m/s) and mixing height (m), is the computed Ventilation, which ranges from about 0 to 15,000 m^2/s. The depth of the mixing layer can be estimated from vertical temperature profiles observed at nearby upper air reporting stations and the values of surface temperatures in the area.

Next, the computed Ventilation (V) is scaled to produce a Ventilation Index (VI), which varies from 0 to 100. The higher the VI, the more effective the smoke dispersion:

$$VI = 9 + 0.02 \times V - 1.7 \times 10^{-6} \times V2 + 6.8 \times 10^{-11} \times V3$$

Environment Canada issues Smoke Control Forecasts, which provide Ventilation Indices, temperatures, mixing heights and wind speeds for both upcoming mornings and afternoons. Spot indices are based on the aspect and elevations of the sites. Heights of inversions and breakthrough temperatures are also given, along

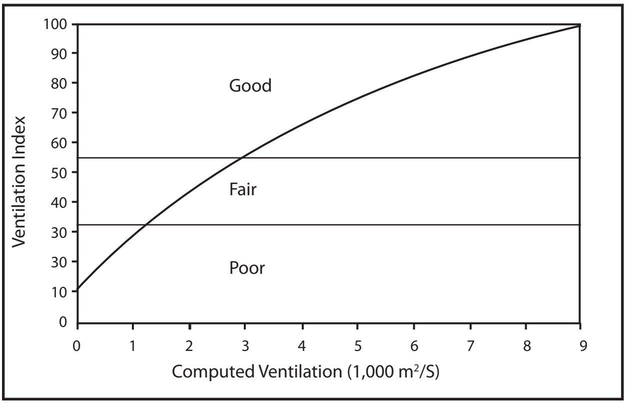

Figure 13: Ventilation Index versus Computed Ventilation.

with a four-day forecast of general venting conditions. These forecasts assist fire suppression and prescribed burning operations by indicating the extent to which smoke will or will not be dispersed. The factors that influence atmospheric stability also influence smoke dispersion. Smoke concentrations in a stable air mass will be higher than those in an unstable air mass due to differences in mixing depth (other conditions being equal). Items of special concern are diurnal variations, inversions, topography and fire intensity.

Health Effects

Carbon monoxide (CO) is given off during incomplete combustion. Unlike most by-products of smoke it is tasteless, invisible and odourless. Haemoglobin's affinity for CO is about 210 times what it is for oxygen and so CO blocks haemoglobin's ability to deliver oxygen throughout the body. As the level of CO in the bloodstream increases, the effects become more and more severe. Behaviour and performance are initially affected, followed by the central nervous system and vision. At higher CO concentrations, cardiac and pulmonary changes occur and eventually headaches and fatigue lead to coma, respiratory failure and death.

Wildland fire fighters should be aware of the hazards associated with working in heavy concentrations of smoke for extended periods. Investigations by the North Carolina Division of Forestry found that smouldering combustion produces high levels of CO. Be alert for complaints of headaches, fatigue or vision problems while on extended fire attack duties.

In addition to CO emissions, wildfire smoke contains potentially hazardous concentrations of particulate matter. Wood smoke particulates are relatively small – 70% are less than 2.5 microns in diameter, 20% are between 2.5 and 10 microns and 10% are greater than 10 microns. Their size distribution varies greatly, depending on the fire's rate of energy release. For example, particulate emissions for high intensity fires have a bimodal size distribution with peaks near 0.3 microns and > 35 microns. For less intense fires, particulate emissions have a normal distribution with the peak near 0.3 microns. Larger particulates in the plumes of high intensity fires are not products of combustion, but rather products of mechanical mixing (turbulence).

The reduction of visibility due to wildfire smoke can have widespread impacts which not only affect the fire suppression operation but also those of other public service organisations, along with public safety. Visibility reduction reduces the effectiveness of fire detection, impairs intelligence gathering, disorients ground forces, compromises the safety and effectiveness of airtanker operations and eventually grounds fire suppression aircraft.

Public health and safety may be compromised by road and airport closures, as well as increased risk during evacuations. Road and airport closures have economic impacts, especially upon tourism. While it is not possible to prevent smoke from wildfires, advanced notice allows for implementation of contingency plans. In addition to concerns about the destructive aspects of wildfires there are potential health problems for people with respiratory conditions as small particulates are carried deep into the lungs.

Fire Prevention

The Ministry of Forests has recorded data about the cause, size and costs of wildfires almost since the inception of fire suppression in this province. These data are analyzed frequently to determine trends in fire causes and locations. Fire prevention strategies are based on these analyses and annual comparisons determine if fire prevention measures are effective.

The prevention of human-caused wildfires is an important function of fire management. Significant cost savings and reduction of undesirable environmental and social impacts result when unwanted wildfires are reduced or eliminated. Preventative measures are applied to the general public and various industrial activities carried out in the forest through legislation which identifies the authority and responsibility to address fire prevention, control and use.

Activity management modifies or restricts human activities in terms of functions, location and timing in relation to the degree of fire hazard and risk. A number of vehicles exist:

1. Fire season: the period from April 1st to October 31st is defined as the official fire season during which most preventative conditions apply.
2. Forest use restrictions: legislation provides for a designated Forest Official to restrict public access and various forest-based industrial activities when fire hazard conditions warrant.

3. Open burning: legislation recognizes the need for the use and application of fire but provisions are made for the restriction, prohibition or extinguishment of open burning when conditions warrant.

Open burning is broken into four broad sections: open fires for cooking, warmth and ceremony; small open fires; large open fires and resource management open fires. A burning reference number is required for larger burns throughout the year. The conditions under which each type of burning may be conducted are specified within the *Forest Fire Prevention and Suppression Regulation*. A number of precautions need to be taken and specific equipment and human resources are required to prevent fires from escaping. All open burns are subject to regulations governing smoke management.

More information on open burning is available at the MoF Protection web site at http://bcwildfire.ca.

Fuel Management

Since 1825, devastating wildfires have taken many lives and destroyed entire communities all over North America as a consequence of failures to manage fuel. Fuel accumulations significantly impact the type and nature of wildfires which threaten settlements and improvements in what is termed the wildland-urban interface.

Controlled burning in BC to reduce fuel levels after forest harvesting dates from the early 1900s, especially on the south coast. In the past two decades, management for biodiversity values (including coarse woody debris retention), public opposition to wildland smoke, and improved harvesting and site preparation technologies have significantly reduced the amount of prescribed burning for silvi-cultural site preparation and hazard reduction. These have been the most common applications for prescribed fire in this province.

Piling and burning of waste wood, rather than broadcast burning, became more popular in the late 1980s. However, in recent years, roughly five times as much Crown land has been treated by mechanical silvicultural site preparation techniques than with prescribed fire. Prescribed burning is also used to improve wildlife habitat, safeguard communities in the wildland-urban interface and restore fire-maintained ecosystems.

Current legislation and regulations require an individual who engages in specified timber harvesting activities to assess the resulting fire hazard. They also enable a designated Forest Official to assess the fire hazard on Crown or private land and order disposal of the hazard if deemed necessary.

Future forest managers will face a number of problems if fuel accumulation continues in some ecosystems. Fires will be more intense and more difficult to manage, forest health problems will continue to escalate, and biodiversity will be reduced as fire-dependent species of plants and animals become scarcer. A lack of strategies to address the accumulation of forest fuels will result in a significant threat to forest resources and rural structures. Future land managers and planners must understand the natural role of fire in the ecosystem and find ways to mimic or apply fire in order to solve these problems.

Fire Detection

The goal of BC's wildfire detection program is to find fires when they are small enough to allow quick initial attack and effective control. Minimizing the lag time between ignition and detection, relative to fire spread rates, is crucial to achieving the current initial attack success rate – containment of 94% of all unwanted wildfires at less than 4 hectares.

There are a number of key components to wildfire detection:

1. Public detection: as the single largest detection group, the public is responsible for reporting approximately 46% of wildfires via a toll-free phone number.
2. Ground patrols: Ministry of Forests' Fire Wardens patrol high risk areas, such as forest recreation sites, during periods of high use and increased fire hazard. These patrols detect approximately 3% of all wildfires but also serve a prevention function by informing the public about the careful use of fire relative to the fire danger. Forest industry personnel may also inspect active forest harvesting areas for potential fire starts, primarily from operating machinery.
3. Aircraft patrols: fixed-wing aircraft were first used in 1921 and usually followed a set patrol route. Using information gathered by the lightning detection and location system, patrol routes now cover specific areas with increased effectiveness and efficiency. Aircraft consistently patrol areas prone to fire activity and detection problems. Aerial detection finds approximately 20% of all wildfires.
4. Lookouts: once considered the mainstay of the detection system, lookouts now play a minor role – detecting approximately 5% of wildfires. Lookouts are still utilized during periods of high hazard where no other detection mechanism is available. A number of lookouts, located in critical or isolated locations, continue to observe areas of high risk and/or high values.
5. Lightning location: the current lightning detection and location system was first used in 1980. Detectors at a number of sites discriminate between cloud-to-ground lightning, cloud-to-cloud lightning and electromagnetic noise. Data are transmitted to a central position analyzer, which calculates the time and location of each lightning strike for display on computer-generated maps at fire control centres throughout the province. The system cannot predict where specific lightning-caused fires will occur but contributes data to computer models that carry out that task.
6. Infrared scanning: hand-held and aerial devices are used extensively to detect heat sources and reduce the number of wildfires resulting from "hangover" landing and pile burns. These fires smoulder for long periods and are undetectable by other means. The result of this technology has been a significant reduction in the area burned, timber damage and fire suppression costs.

Fire Reporting

Reporting wildfires is a final crucial step in the fire detection process. A centralized fire reporting centre gathers information through the 1-800-663-5555 toll-free number and electronically transfers that information to the responding fire centre. Forest industry personnel and aircraft flight services also report wildfires through their respective communication networks.

It is important to collect and report accurate information about fire size, location and behaviour; weather conditions; fuel types; topography; access; and property and resource values. These data are entered into a computer and transferred to the appropriate fire centre, where personnel determine the appropriate response for each wildfire.

Fire Fighter Safety

Fighting fire is a dangerous occupation. The first responsibility of fire fighters is to prevent injury to themselves and others. Safety is of paramount importance, cannot be over-emphasized and must not be compromised – even if homes and commercial values are threatened. Homes should be insured and can be rebuilt. The natural environment is resilient and will recover from wildfire, people cannot.

The fire crew boss looks after the crew's safety and welfare 24 hours a day and ensures they are productive. The crew boss must be alert and know where the fire is at all times and what it is doing, as well as the location of all crew members. An up-to-the-minute escape route must be identified. Know what danger signs to look for, including crew fatigue, and know when to take a break. The crew boss must think before acting and then act decisively, assigning the most experienced crew members to key positions and keeping the crew informed of all activity and progress.

Fire fighters should always work by these rules: stay with the crew boss and follow all instructions; stay at least 3 metres apart while working or hiking; and watch where you're going. Never walk near, or work beneath, a burning dead tree or trees with fire-weakened root systems. Watch for rolling rocks or debris on steep slopes and never work below a bulldozer or another crew. If you see something dangerous, shout out and warn your crewmembers. Let everyone know if the fire jumps the fire guard. Follow the WATCH OUT guidelines:

Weather	dominates fire behaviour, so keep informed
Action	must be based on current and expected fire behaviour
Try out	at least two safe escape routes
Communications	should be maintained with crew, boss and adjoining forces
Hazards	watch for grass fuels, chimneys and snags
Observe	changes in wind direction, velocity, and clouds
Understand	your instructions and make sure yours are understood
Think	clearly, be alert, and act decisively before your situation becomes critical

The fire environment is such that some fires are impossible to control. Extreme fire behaviour may occur, for example, when a fire encounters plentiful and dry fuels or when wind speeds increase with the passage of a cold front. The safety of the crew is paramount, and the crew boss must expect the unexpected.

Two escape routes and a safety zone must be established before a fire is attacked. Provided that standing dead and burned trees do not present a hazard, a burned-over area free of other fuels can be used as a safety zone. Heavy equipment can construct safety zones at specified intervals along the fireguard. Escape routes and safety zones must be confirmed or re-established on a regular basis and all crew members kept informed.

Air support is a valuable tool for the fire fighter, but it brings dangers to the fireline. The bird-dog aircraft makes at least one pass before an air tanker drop to provide a warning. Fire fighters on the ground must keep out of the drop area and clear out any branches or dead trees that could be an overhead hazard.

Community Safety

BC has one of the fastest-growing rural populations in North America. Many people are leaving the city to live in forested areas. But living in the wildland-urban interface, the area where forests and communities meet, means living with fire and yet residents are rarely prepared for the serious wildfires that destroy homes, property and lives.

To mitigate the impacts of wildfire, action must be taken well in advance. A home's chances of survival are greatly improved through careful location, design and maintenance. Homes should be sited where potential fire behaviour is minimized and also be surrounded by a fuel-free zone. Appropriate landscaping reduces the fire hazard, with deciduous trees being better than conifers. The forest beyond the fuel-free zone, up to several hundred metres away, should be evaluated and treated if necessary. Fire intensity is reduced where less fuel is available.

Roofs can be made of fire-resistant material rather than highly-flammable shakes or shingles. Deck supports should be made of non-combustible materials or encased. Deck surfaces should also be non-combustible. Exterior siding, windows and vents are probably more vulnerable than the roof to intense heat. When a fire is close enough, its heat and flames directly threaten the home, causing combustible materials to ignite. The intense heat of a wildfire can also melt plastics, including vinyl siding, and break windows.

Burning embers or firebrands can be carried by the wind for several kilometres to land on roofs or collect in low points around a house. Embers can be drawn inside if there are open eaves or unscreened windows and vents. Firebrands can lodge in the exterior siding and structure loss is likely unless the siding is fire-resistant. Windows should be double-paned and be at least 10 metres away from trees or flammable shrubs

Every home should have a clearly-visible address sign, adequate road access for emergency response vehicles and provide for fire fighter safety zones and escape routes. Homeowners must ensure that the roof and gutters are free of leaves, needles and other debris; have fire-fighting tools on hand; have a water hose that is able to reach all exterior walls, and the roof; and have a home and area evacuation plan.

Rural developments often lack building restrictions, provisions for fire protection or roads suitable for the movement of heavy fire-fighting equipment. Residents of rural or forested areas play a key role in wildfire protection and are responsible for their buildings and property. The BC Forest Service is concerned about residents living in forested areas and will take action to prevent loss of life or the spread of fire to or from structures. However, Forest Service personnel are not equipped or trained to fight structure fires.

Effective wildfire prevention and control in the wildland-urban interface requires co-operation between municipal and rural fire departments, the Forest Service, developers and homeowners. The insurance industry is becoming more and more proactive due to multi-million dollar insurance claims resulting from fires in the wildland-urban interface.

Legislation, Policy and Procedures

The *Ministry of Forests Act*

The *Ministry of Forests Act* mandates the Ministry of Forests to "encourage maximum productivity of the forest and range resources in British Columbia" and to "manage, protect and conserve the forest and range resources of the government, having regard to the immediate and long term economic and social benefits they may confer on British Columbia" (RSBC, 1996). This act gives broad direction to the ministry's programs and forms the environmental and socio-economic bases for protection of the natural resources from the unwanted effects of wildfires.

The *Forest Practices Code of British Columbia Act*

The *Forest Practices Code of British Columbia Act* was passed in July 1994 and took effect on June 15, 1995 (SBC, 1994). The act is the legal umbrella that authorizes all of the components of the Forest Practices Code. It provides the mandatory requirements for forest practices, sets out enforcement and penalty provisions and outlines supporting procedures and administrative bodies such as the Forest Practices Board and the Forest Appeals Board.

The *Forest Practices Code of British Columbia Act* allows for standards which expand on regulatory requirements. Supporting the act, regulations and standards, but not embodied in legislation, are guidebooks. Their purpose is to help users exercise their professional judgement to develop site-specific strategies and prescriptions. They provide recommended procedures, processes and results for forest practices. These provisions become enforceable only when they are included in plans, prescriptions or contracts or when incorporated by reference in the regulations.

Part 5 of the *Forest Practices Code of British Columbia Act* outlines protection of forest resources. Sections 75 through 95 cover fire use, hazard assessment and responsibilities, fire suppression, duty to report a forest fire, government jurisdiction and compensation. Many or most of the fire-related provisions of this act and its regulations were formerly part of the *Forest Act* and its regulations.

Forest Fire Prevention and Suppression Regulation

The *Forest Fire Prevention and Suppression Regulation* is one of 20 regulations established under the *Forest Practices Code of British Columbia Act*. This regulation requires every person working in or within 1 kilometre of a forest to provide suitable fire-fighting equipment. The kind and amount of equipment varies with the type of activity being conducted, the time of year the activity is performed and the number of persons employed at the worksite of the activity.

Fire regulations have undergone a number of significant changes over the years. These changes have included combining the *Fire Precautions in Relation to Railways, Forest Fire Prevention Regulation, Snags and Slash Disposal and the Campfire Regulation*. The *Forest Fire Prevention and Suppression Regulation* was introduced in 1995. The elimination of both Class 'B' burning permits in 1994 - 1995 and Class 'A' burning permits in 1998 made way for a more efficient system for administration of open fires.

Other changes were made regarding the fire equipment required in helicopter logging operations and the submission of fire preparedness plans in order to ensure efficiencies and keep in step with changes in the forest industry.

For further information: www.for.gov.bc.ca/tasb/legsregs/
http://bcwildfire.ca/

Integrating Fire and Land Management

Wildfires are the most prevalent natural disturbance in BC and demand both our understanding and our respect. Wildfires promote plant and animal diversity by maintaining structural complexity within stands and by influencing the composition, size, edge characteristics and distribution of stands across the landscape. Most grassland and forested ecosystems in BC are influenced by wildfire, which may select for or against particular plants and animals – within populations, among species, in ecosystems and on the landscape.

There are differences between natural fire regimes and those implemented by resource managers. A role for natural and/or prescribed fire may be possible in protected areas and ecological reserves, and in other forested areas under certain circumstances. The challenge to resource and fire managers is one of including and excluding the appropriate type, location and quantity of both natural and prescribed fires on the various landscapes of this province, in consideration of resource, community and wilderness values.

Technological improvements in fire detection and suppression have greatly enhanced our abilities to manage fire but attention must always be paid to the long-term environmental effects of fire inclusion or exclusion and the economic and social costs and benefits of fire management policies and practices.

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FOREST PEST MANAGEMENT

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FOREST PEST MANAGEMENT

Introduction

Much of the annual harvesting of timber in British Columbia (BC) is determined by insects, the most notable of which are the bark beetles that attack pines, spruces, Douglas-fir and subalpine fir. These insects compete directly with foresters for the mature trees that yield the major timber volumes as felling is directed into infested stands in an effort to utilize as much of this timber as possible. In addition, their role as natural disturbance factors leads to unplanned major changes in forested landscapes. In 2003, a major outbreak of the mountain pine beetle in lodgepole pine forests of central BC extended over more than 5.7 million hectares affecting 108 million m^3 of timber worth more than $9 billion. Some licensees presently carry out their whole annual harvesting in beetle-infested stands.

While bark beetles are the spectacular and obvious symptoms in an affected forest, the root rots and other diseases also have a serious impact on the mature forest as well as determining the options for reestablishment of the new forest. *Armillaria ostoyae* is of major significance in the southern and central parts of BC, *Phellinus weirii* in coastal BC and *Inonotus tomentosus* in the spruce dominated ecosystems of northern BC. Insects and diseases impact all aspects of our forest management from seedling establishment through to maintenance of old growth areas. Cone and seed insects and pathogens can greatly reduce seed production and in so doing greatly reduce the return on high investment, superior, genetically improved crosses. In the wood damaging category, ambrosia beetles excavate darkly stained galleries in the sapwood and thereby degrade lumber values. In high grade sawlogs, these losses are in the range of $70 to $80 per m^3 (Orbay *et al.* 1993). In coastal BC this represents an annual loss of $44 million. In addition, bark and wood boring insects are important quarantine problems in export markets.

The objectives of this chapter are to provide an introduction and general overview of the topic of forest pest management in BC. Insects, diseases, abiotic factors and animal damage that affect the forest are currently termed forest health factors (FHFs). In this chapter we provide concise practical summaries for certain aspects of forest health and guide you to the best available information on most forest health factor problem situations you might encounter in the field.

Federal, provincial and individual licensee responsibilities for surveying and managing forest health

The function of recording and summarizing data on the cause, location and severity of insects and disease outbreaks in BC was carried out by the Forest and Insect Disease Survey (FIDS) of the Canadian Forest Service (CFS) from 1914 through 1995. In 1980, the BC Ministry of Forests (BCMOF) established regional pest management personnel who were responsible for translating these survey data into meaningful management strategies (McLean, 1994). In 1995, the *Forest Practices Code of BC Act* was enacted in BC. It was supported by a series of very useful Forest Practices Code Guidebooks on pest management issues including Bark Beetle Management, Defoliator Management, Root Disease Management and Dwarf Mistletoe Management. These guidebooks encapsulate the state of knowledge on life histories, surveys and management options for these pest groups as of 1995.

The *Forest Practices Code of BC Act* was consolidated in December, 2002, and a new *Forest and Range Practices Act* (FRPA) enacted. The regulations for this act are currently under development but will include Defined Forest Area Management guidelines that will describe licensee obligations within Timber Supply Areas. Forest Health strategies, especially issues in Beetle Management Units (BMUs), will also be closely defined.

Recent reorganization of the BCMOF has resulted in the creation of three administrative regions (Coastal, Northern Interior, and Southern Interior) as of April 1, 2003, in place of the original six (Cariboo, Kamloops, Nelson, Prince George, Prince Rupert, and Vancouver). Pest management issues will continue to be coordinated by the Forest Practices Branch which has now assumed the responsibility for providing annual overview data on the condition of the provincial forest and relating it to historical trends and projections of future losses. Licensees will be increasingly responsible for pest management activities. They are required to produce a Forest Health Strategy for their operating area that will meet the requirements outlined in the Provincial Forest Health Strategy. You will need to follow the new BCMOF organizational developments by visiting ministry web sites as the *Forest and Range Practices Act* regulations are formulated over the next two years (see: www.for.gov.bc.ca/hcp/fia/landbase/).

Forest Health Factors

The major forest health factor (FHF) groupings in BC are bark beetles, defoliators, diseases, abiotic factors and animals. In 2003, bark beetles were the major FHF (Figure 1), notably the mountain pine beetle on lodgepole pine in the Northern Interior. Other significant FHFs were the western spruce budworm on Douglas-fir and pine needle cast on lodgepole pine. Data on abiotic damage and animal damage are also collected routinely.

Important commercial tree species and their occurrence in biogeoclimatic zones

As background, we list the names and symbols for commercial tree species (Table 1) and the major biogeoclimatic zones in BC including major tree species (Table 2).

Forest health factor codes

The BCMOF has developed standardized three letter codes for most FHFs to facilitate consistent recording in survey forms. An overview of these codes and specific notable examples are given in Table 3. The occurrence rating for major FHFs in each biogeoclimatic zone is provided in Table 4. Field codes are given along with common names and scientific names for each FHF.

Table 1: Names and symbols for tree species in the forests of BC.[a]

Tree name		Tree symbol	
Common name	**Scientific name**	**Genus**	**Species**
CONIFER			
True Fir (Balsam)	***Abies***	**B**	
amabilis fir	*A. amabilis*		Ba
grand fir	*A. grandis*		Bg
subalpine fir	*A. lasiocarpa*		Bl
noble fir	*A. procera*		Bp
Cedar	***Thuja***	**C**	
western redcedar	*T. plicata*		Cw
Cypress	***Chamaecyparis***	**Y**	
yellow cedar	*C. nootkatensis*		Yc
Douglas-fir	***Pseudotsuga***	**F**	
Douglas-fir	*P. menziesii*		Fd
Hemlock	***Tsuga***	**H**	
mountain hemlock	*T. mertensiana*		Hm
western hemlock	*T. heterophylla*		Hw
Larch	***Larix***	**L**	
alpine larch	*L. lyallii*		La
tamarack	*L. laricina*		Lt
western larch	*L. occidentalis*		Lw
Pine	***Pinus***	**P**	
whitebark pine	*P. albicaulis*		Pa
limber pine	*P. flexilis*		Pf
jack pine	*P. banksiana*		Pj
lodgepole pine	*P. contorta*		Pl
western white pine	*P. monticola*		Pw
ponderosa (yellow) pine	*P. ponderosa*		Py
Spruce	***Picea***	**S**	
black spruce	*P. mariana*		Sb
Engelmann spruce	*P. engelmannii*		Se
Sitka spruce	*P. sitchensis*		Ss
white spruce	*P. glauca*		Sw
hybrid spruce	*Picea* hybrids		Sx
Yew	***Taxus***	**T**	
western yew	*T. brevifolia*		Tw
BROAD-LEAFED TREES			
Alder	***Alnus***	**D**	
red alder	*A. rubra*		Dr
Arbutus	***Arbutus***	**R**	
arbutus[b]	*A. menziesii*		Ra
Aspen, Cottonwood, or Poplar	***Populus***	**A**	
trembling aspen	*P. tremuloides*		At
black cottonwood	*P. balsamifera* ssp. *trichocarpa*		Act
balsam poplar	*P. balsamifera* ssp. *balsamifera*		Acb

Birch	***Betula***	**E**	
common paper birch	*B. papyrifera*		Ep
Dogwood	***Cornus***	**G**	
pacific (western flowering) dogwood[b]	*C. nuttallii*		Gp
Maple	***Acer***	**M**	
bigleaf maple	*A. macrophyllum*		Mb
Oak	***Quercus***	**Q**	
Garry oak	*Q. garryana*		Qg
Willow[b]	***Salix***	**W**	

[a] Ministry of Sustainable Resource Management Terrestrial Information Branch. June 2002. Forest Inventory and Monitoring Program, Growth and Yield, Standards and Procedures, Appendix 3: Species symbols, names and symbols for tree species in BC.

[b] Non-commercial species.

Table 2: Biogeoclimatic ecosystems of BC, and their most abundant tree species.[a]

Biogeoclimatic ecological zone		**Tree species[b] present in zone, listed in order of relative abundance from dominant to less abundant**
AT	Alpine Tundra	Krummholz only
BG	Bunchgrass	Mostly grasses and shrubs
BWBS	Boreal White and Black Spruce	At, Sw, Pl, Sb, Acb, Lt
CDF	Coastal Douglas-fir	Qg, Ra, Fd, Pl, Bg, Cw, Mb, Gp
CWH	Coastal Western Hemlock	Hw, Cw, Ba, Yc, Fd, Bg, Pw, Ss, Mb, Gp
ESSF	Engelmann Spruce–Subalpine Fir	Se, Bl, Pl, Pa, Pf, La
ICH	Interior Cedar–Hemlock	Hw, Cw, Fd, Lw, Pl, Pw, At, Ep, Bl, Se, Tw
IDF	Interior Douglas-fir	Fd, Py, Sw, Pl
MH	Mountain Hemlock	Hm, Ba, Yc, Hw, Cw, Fd, Pw, Pl
MS	Montaine Spruce	Sx, Pl, Bl, Fd, Lw, Cw, At, Act
PP	Ponderosa Pine	Py, Fd, At
SBPS	Sub-Boreal Pine–Spruce	Pl, Sw, Sx, Bl, Fd, Sb, Act
SBS	Sub-Boreal Spruce	Sx, Bl, Sb, Pl, Fd, At, Ep, Act
SWB	Spruce–Willow–Birch	Sw, Bl, Pl, At, W (several spp.), scrub birch (*Betula glandulosa),* Sb, Acb

[a] Based on The Biogeoclimatic Zones of BC, brochure series of 14 booklets, each individually titled "The Ecology of [one of the BGC Zones of BC]" (1996-1999, BCMOF). The brochures are accessible online, along with a map that shows the geographic distribution of each zone, at the Biogeoclimatic Zones of British Columbia website: www.for.gov.bc.ca/hfd/library/documents/treebook/biogeo/biogeo.htm See also Pojar and Meidinger (1991).

[b] See Table 1 for tree species symbols.

Table 3:
Overview of two- or three-letter field codes used to record forest health factors on field survey forms by the BCMOF. All major categories are summarized below, along with examples[a].

Field code		Forest health factor description and example	
A		**ANIMAL DAMAGE**	
AC		cattle	*Bos taurus*
C		**CONE AND SEED INSECTS**[2]	
	CBC	Douglas-fir cone moth	*Barbara colfaxiana*
	CLO	western conifer seed bug	*Leptoglossus occidentalis*
D		**DISEASES**	
DB		Broom Rust	
	DBF	fir broom rust	*Melampsorella caryophyllacearum*
DD		Stem Decays	
	DDE	rust-red stringy rot	*Echinodontium tinctorium*
DF		Foliage Diseases	
	DFE	elytroderma disease	*Elytroderma deformans*
DL		Leader or Branch Diebacks	
	DLP	phomopsis canker	*Phomopsis lokoyae*
DM		Dwarf Mistletoes	
	DMF	Douglas-fir dwarf mistletoe	*Arceuthobium douglasii*
DR		Root Diseases	
	DRA	armillaria root disease	*Armillaria ostoyae*
DS		Stem Disease (Canker or Rust)	
	DSA	atropellis canker	*Atropellis piniphila*
I		**INSECTS**	
IA		Aphids or Adelgids	
	IAB	balsam woolly adelgid	*Adelges piceae*
IB		Bark Beetles	
	IBB	western balsam bark beetle	*Dryocoetes confusus*
ID		Defoliating Insects	
	IDA	black army cutworm	*Acetbia fennica*
IS		Shoot Insects	
	ISB	western cedar borer	*Trachykele blondeli*
IW		Weevils	
	IWC	conifer seedling weevil	*Steremnius carinatus*
M		**MITE DAMAGE *(TRISETACUS SPECIES)***	
N		**NON-BIOLOGICAL (ABIOTIC) INJURIES**	
NG		Frost	
	NGK	shoot/bud frost kill	
P		**CONE AND SEEDLING FUNGAL PATHOGENS**[b]	
	PSS	sirococcus tip blight	*Sirococcus strobilinus*
	PDT	cedar leaf blight	*Didymascella thujina*
T		**TREATMENT INJURIES**	
TP		Planting	
	TPM	planting-poor microsite	
V		**PROBLEM VEGETATION**	
VH		Herbaceous Competition	

[a] Complete lists of codes (including damage agents of cones, seeds, and seedlings) are available in: Ministry of Sustainable Resource Management Terrestrial Information Branch. June 2002. Forest Inventory and Monitoring Program, Growth and Yield, Standards and Procedures, Appendix 14: Damage Agents and Severity Codes.

[b] Most codes are also tabulated in a field reference that may be frequently encountered in BCMOF publications and websites: BCMOF field card FS 747 Damage Agent and Condition Codes. 1999. BCMOF.

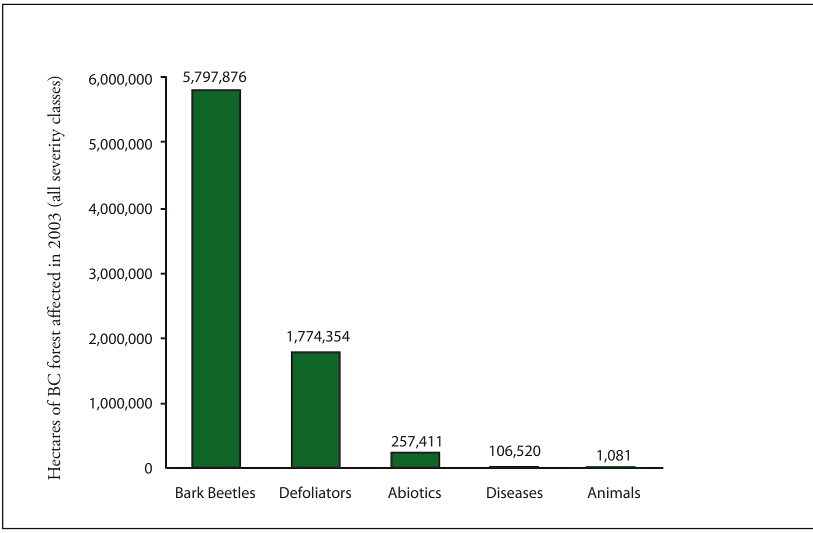

Figure 1:
Major forest health factors in the forests of BC as detected by aerial surveys in 2003. The significance of tree diseases is underestimated by aerial surveys alone, as aerial surveys detect only foliage diseases, but not root diseases, dwarf mistletoes, decays and butt rots, and stem rusts.

You will have noticed in Table 3 that FHFs are listed in nine major categories: animal damage (A-), cone and seed insects (C--), diseases (D--), insects (I--), mite damage (M), non-biological (abiotic) injuries (N--), cone and seedling pathogens (P--), treatment injuries (T--) and problem vegetation (V-).

The animal damage codes are straightforward and you can see the detailed list in Table 4. Cone and seed insects and cone and seedling pathogen subcodes are based on the scientific name of the organism. For example, the Douglas-fir cone moth, *Barbara colfaxiana*, is coded C for cone and seed insect and BC based on its scientific name, for a three letter code of CBC. The sirococcus tip blight is coded P as a Cone and Seedling Pathogen and SS for *Sirococcus strobilinus* for a three letter code of PSS. The disease FHFs (D--) are grouped by similar types. Thus broom rusts are DB- and the fir broom rust specifically is DBF. Other major disease groupings include the decays (DD-) that are saprophytic fungi that degrade wood through

Table 4: Relative incidence of forest health factors by biogeoclimatic zone in British Columbia.

Type of damage (common name, damage agent code, scientific name)	**Host(s)**[a, b]	**Occurrence in biogeoclimatic zones**[c, d]										
		CDF	**CWH**	**MH**	**ESSF**	**IDF**	**PP**	**SBS**	**SBPS**	**BWBS**	**ICH**	**MS**
A. Insects												
balsalm woolly adelgid IAB *Adelges piceae*	**Ba**, **Bg**, B-	**H**	**H-L**									
black army cutworm IDA *Actebia fennica*	All conifer seedlings (Ba, Bl, Cw, Fd, Hw, **Pl**, Pw, Si, **Sw**, Sx)				**L**			**M-L**	**L**		**L**	
conifer seedling weevil IWC *Steremnius carinatus*	B-, Cw, **Fd**, Hw, **Ss**		**H-L**									
Douglas-fir beetle IBD *Dendroctonus pseudotsugae*	**Fd**, Lw		**H**		**L**	**H-M**	**H-L**	**H-M**	**M-L**		**H-L**	**H-L**
Douglas-fir tussock moth IDT *Orgyia pseudotsugata*	**Fd**, Lw, Pl					**H-M**	**H-L**				**M**	
eastern spruce budworm IDE *Choristoneura fumiferana*	**Bl, Se, Sw**									**H**		
lodgepole pine terminal weevil IWP *Pissodes terminalis*	**Pl**				**?**	**M**					**?**	
mountain pine beetle IBM *Dendroctonus ponderosae*	Pa, **Pl**, Pw, Py		**H**		**H-L**	**H-L**	**M-L**	**H-L**	**H-L**	**L**	**H-L**	**H-M**
pitch moth ISP *Petrova albicapitana*	**Pl**	**H**	**H**									

red turpentine beetle IBT *Dendroctonus valens*	**Pl**, **Py**					**?**	**M**					
spruce beetle IBS *Dendroctonus rufipennis*	Pl, Sb, **Se**, Si, **Ss**, **Sw**, Sx		**H-L**		**H-L**	**L**		**H-L**	**M**	**H-L**	**H-L**	**H-L**
Warren's root collar weevil IWW *Hylobius warreni*	**Pl**, Si										**?**	
western balsalm bark beetle IBB *Dryocoetes confusus*	Ba, **Bl**, Pl, Se, Sw			**?**	**H**			**H-M**	**M**	**M-L**	**M**	
western hemlock looper IDL *Lambdina fiscellaria lugubrosa*	Bl, Cw, Hm, **Hw**, Se, Si, Sx		**?**		**H-L**						**H-L**	
western pine beetle IBW *Dendroctonus brevicomis*	**Py**						**M**				**?**	
western spruce budworm IDW *Choristoneura occidentalis*	**Fd**, Lw, Pl, Sx		**H**		**M-L**	**H-L**	**H-L**				**H-L**	**M-L**
white pine (spruce) weevil IWS *Pissodes strobi*	P-, **Se**, Si, **Ss**, **Sw**, Sx	**H**	**H-L**		**M-L**	**H**		**H-L**	**M**	**L**	**H-L**	**M-L**
B. Diseases												
annosus root disease DRN *Heterobasidion annosum*	High susceptibility: Ba, Hw, Ss. Secondary hosts: Cw, Fd, Pl. Other hosts (from free growing guide): Bg, Se.	**L**	**M-L**	**?**	**M**	**?**					**?**	
armillaria root disease DRA *Armillaria ostoyae*	**Ba, Bg, Bl, Cw, Fd, Hw, Lw, Pl, Pw, Py, Si, Sx, Se, Ss** (essentially all tree sp.)	**M-L**	**H-L**	**?**	**H-L**	**H-L**	**H-L**	**H-L**	**M-L**		**H-L**	**H-L**

Table 4 (cont'd)

Type of damage (common name, damage agent code, scientific name)	**Host(s)**[a, b]	**Occurrence in biogeoclimatic zones**[c, d]										
		CDF	**CWH**	**MH**	**ESSF**	**IDF**	**PP**	**SBS**	**SBPS**	**BWBS**	**ICH**	**MS**
black stain root disease DRB *Leptographium wageneri*	**Fd**, Pl, Pw, Py, S-	**L**	**L**			**?**	**L**				**H-L**	**M**
brown crumbly rot DDF *Fomitopsis pinicola*	Pl; B-, Se, Sw, Ss, Pl, Pw, Py, Fd, Cw, Hw, Hm, Lw				**L**							
comandra blister rust DSC *Cronartium comandrae*	**Pl, Py** (Alternate hosts: *Comandra* spp. or *Geocaulon* spp.)				**M-L**	**L**		**H-L**	**M-L**	**M-L**	**H-L**	**H-L**
Douglas-fir dwarf mistletoe DMF *Arceuthobium douglasii*	**Fd**; Bg					**H-L**	**H-M**				**L**	
hemlock dwarf mistletoe DMH *Arceuthobium tsugense*	Hm, **Hw;** Ba, Bl, Plc, Ss		**H-L**	**M**							**L**	
laminated root rot DRL *Phellinus weirii*	High susceptibility: **Ba**, **Bg**, **Fd**, **Hm**. Moderate susceptibility: Bl, Hw, Lw, Pl, Pw, Py, Ss, Se, Si, Sx. Partially resistant: Cw	**H**	**H-L**		**M-L**	**H-L**	**L**	**L**			**H-L**	**L**
larch dwarf mistletoe DML *Arceuthobium laricis*	Pl, **Lw**; Pw, Bg					**H-L**	**?**				**H-L**	**H-M**
lodgepole pine dwarf mistletoe DMP *Arceuthobium americanum*	Pl, Py				**M-L**	**H-L**	**L**	**H-M**	**H**	**H**	**H-L**	**H-M**
pini (red ring) rot DDP *Phellinus pini*	Bl, Cw, Pl, Fd, Hw, Pw, Se, Si, Sw, Ba, Ss, Sx; P-, S-, Lw, Fd, Cw., B-, Yc, Hm		**M-L**	**?**	**H-L**			**H-L**	**M**	**H-M**	**H-L**	

rhizina root disease DRR *Rhizina undulata*	Bl, Bg, Cw, Fd, Hw, Lw, Pl, Pw, Py, Sx; essentially all native conifer sp. seedlings	**?**		**L**	**H-L**		**L**			**H-L**	**H**
rust-red stringy rot DDE *Echinodontium tinctorium*	Ba, Bl, Hw, Pl, Sw; B-, H-, Fd, S-, Cw	**H-M**	**?**	**H**			**H-M**	**M**	**H-M**	**H**	
schweinitzii butt rot DDS *Phaeolus schweinitzii*	Fd, Hm, Lw, Pl, Py, Sx; Hw, Ba, Bl, Ss, Sw, Lw, Lt, Pl, Pw, Cw, Garry oak			**L**	**H**	**M**				**H**	**L**
stalactiform blister rust DSS *Cronartium coleosporioides*	**Pl, Py**; (Alternate hosts: *Castilleja* spp., Family Scrophulareacea)			**M-L**	**L**		**H-L**	**M-L**	**M**	**M-L**	**H-L**
tomentosus root rot DRT *Inonotus tomentosus*	High susceptibility: Se, Si, Sw, Sx. Moderate susceptibility: Bl, Fd, Hw, Pl, Ss. Part resistant: Cw, broadleaf sp.	**L**		**M-L**	**?**		**H-L**	**M**	**H-L**	**M-L**	**H-L**
western gall rust DSG *Endocronartium harknessii*	Fd, **Pl, Py**			**M-L**	**H-L**		**H-M**	**H-M**	**H-M**	**H-L**	**H-L**
white pine blister rust DSB *Cronartium ribicola*	Pw, Pa, Pf (Limber Pine) (Alternate hosts: most *Ribes* spp.)	**?**		**M**	**M**					**H-M**	

C. Animals

hare/rabbit AH *Lepus americanus*/*Sylvilagus* spp.	all conifer tree spp. are susceptible; Bl, Cw, Fd, Hw, Lw, **Pl**, Pw, Py, Se, Si, Sw, Sx			**H-L**	**L**	**L**	**H-L**	**L**	**H**	**H-L**	**L**

Table 4 (cont'd)

Type of damage (common name, damage agent code, scientific name)	**Host(s)**[a, b]	**Occurrence in biogeoclimatic zones**[c, d]										
		CDF	**CWH**	**MH**	**ESSF**	**IDF**	**PP**	**SBS**	**SBPS**	**BWBS**	**ICH**	**MS**
moose AM *Alces alces*	all tree spp. are susceptible; **Ba**, Bl, **Cw**, Pl, Sw, Sx		**H**		**H**			**H**				
deer AD *Odocoileus* spp.	all tree spp. are susceptible; **Ba**, Bl, Bg, **Cw**, Fd, Hw, Lw, Pl, Pw, Py, Sx	**H**	**H**		**L**	**H-L**	**L**				**H-L**	**H-L**
porcupine AP *Erethizon dorsatum*	Ba, Bl, Cw, **Fd**, **Hw**, Hm, Lw, Pl, Pw, **Py**, **Ss**, Sw, Sx		**M-L**	**?**	**M-L**	**M-L**	**L**	**L**		**L**	**M-L**	**M-L**
squirrel AS *Tamiasciurus hudsonicus*	Bg, Bl, Cw, E, Fd, Hw, Lw, **Pl**, Pw, Py, Sx				**H-L**	**M-L**	**L**	**H-L**	**L**	**H**	**H-L**	**M-L**
cattle AC *Bos taurus*	all tree spp. are susceptible; Ba, Bl, **Fd**, **Pl**, **Py**										**H**	
vole AV *Microtus* spp.	Act, Ba, Bg, Bl, Cw, **Fd**, **Hw**, Lw, Pl, Pw, Py, S, **Ss**, Sw, **Sx**	**H**	**H-L**		**L**	**H-L**	**L**	**M-L**	**L**		**L**	**L**
D. Abiotica												
frost NG	All trees of all ages are susceptible; Cw, **Fd**					**M-L**	**M**				**M**	**H-M**
Shoot/bud frost kill NGK	Bl, Cw, Fd, Hw, (**Pl**), Pw, Se, Si, Sw, Sx				**H-L**			**H-M**		**M-L**	**L**	

[a] See **Table 1** for tree name symbols.
[b] Tree species in bold are the primary hosts, or where the most damage is present.
[c] See **Table 2** for biogeoclimatic zone abbreviations.
[d] % occurrence: **L** = Low (1 - 32%), **M** = Medium (33 - 65%), **H** = High (66 -100%), **?** = Uncertain. Ratings in these tables were developed from "Appendix 6, Regionally Organized Provincial Forest Health Charts" in each of the six regional Forest Practices Code Establishment to Free-Growing Guidebooks (Cariboo, Kamloops, Nelson, Prince George, Prince Rupert, and Vancouver Forest Regions), 1995, BCMOF and Ministry of Environment, Victoria, BC.

the action of their enzymes. Foliage diseases (DF-) include needle casts and blights. Leader diebacks (DL-) include the phomopsis canker (DLP). Dwarf mistletoes (DM-) are parasitic vascular plants that colonize their host and live in the bark of branches and stems as does hemlock dwarf mistletoe (DMH). Root diseases (DR-) are caused by pathogenic fungi such as *Armillaria ostoyae* (DRA) that infests the root collar. These diseases are readily vectored by insects such as the root collar weevils. Finally, there are the stem diseases including cankers or rusts (DS-) such as the western gall rust (DSG).

The insect FHFs (I--) are similarly classified into several major groupings. The first is the aphids and adelgids (IA-). These insects have sucking mouthparts that enable them to plug into the tree's vascular system, as does the balsam woolly adelgid (IAB). Bark beetles (IB-) are the most economically important group of insects, see earlier discussion on the mountain pine beetle (IBM). Here the third letter is coded often in relation to the host so that the (western) balsam bark beetle is IBB and the Douglas-fir beetle is IBF. Defoliating insects (ID-), mainly caterpillars in the order Lepidoptera (moths and butterflies) and Hymenoptera (sawflies) are coded by a unique characteristic. The eastern spruce budworm is IDE while the western spruce budworm is IDW. The black army cutworm is coded as IDA as its scientific generic name is *Actebia* (also the A in army?). The shoot infesting insects (IS-) include many different examples from several different orders. The example here is the pitch moth (ISP) *Petrova albicapitana,* on lodgepole pine. The last insect grouping is the weevils (IW-). These beetles have long snouts and are in the family Curculionidae. They inflict damage in nurseries and in young plantations when they attack around the root collar, as does the conifer seedling weevil (IWC). One of the most notorious members of this group is the white pine/spruce weevil (IWS) which attacks the leaders of spruce trees throughout BC causing serious damage to tree form.

It is always important to remember that climatic conditions can also adversely affect a tree, especially late season frosts (NG-) that kill the tender tissues in expanding buds (NGK). Excessive heat, drought, sunscald, flooding, wounding, and general decline can be recorded in this category. Associating the cause with the effect which shows up much later is quite a challenge.

Some major information sources

Over the last decade a series of very useful publications have been prepared to aid in the identification of FHFs. The web based resources that you might find most useful include:

Field Guide to Forest Damage in British Columbia, 2^{nd} Edition by J. Henigman, T. Ebata, E. Allen, J. Westfall, and A. Pollard. March 2001. BCMOF/Canadian Forest Service Joint Publication No. 17. Victoria BC. 370 pp. This is a very useful handbook (hereafter referred to as JP17) that has been prepared with one forest health factor per page in a ring binder format. It is printed in colour on waterproof paper. This volume is designed to be carried in the field and provides a valuable on-site resource. Hard copies can be purchased through Crown Publications at www.crownpub.bc.ca/.

On the website of the Pacific Forestry Centre of the Canadian Forestry Service there are two very useful online resources:

HForest: Hypermedia Forest Insect and Disease Knowledge Base and Diagnosis by A. Thompson, D, Shaykewich and R. Banfield. Damage agent information can be assessed by way of common name or scientific name, by signs and symptoms in a problem diagnosis function, or by host tree. Adobe PDF versions of the well-respected Forest Pest Leaflet Series are also linked to by HForest.

Tree Doctor by D. Corrin, N.E. Alexander, A. Speed and T. Ebata. This comprehensive guide to forest health factors was developed at Malaspina College in collaboration with the Ministry of Forests. Tree Doctor is a very comprehensive undertaking that covers pest information, diagnostics, hazard and risk to the host tree at the ecological subzone level and free growing survey support. It also includes a rich series of images. Management guidelines link directly to the Forest Practices Code Guidebooks. A glossary based on PesTerms (Doliner and Borden, 1984) is also included.

See also major texts listed in the bibliography at the end of this chapter.

Forest Health in the New FRPA

The new policy framework being developed by the BCMOF will establish obligations and opportunities for collaborative forest management within the province's 37 Timber Supply Areas (TSA). This is termed the Defined Forest Area Management (DFAM) initiative and is designed to transfer more stewardship responsibilities from government to the volume-based tenure holders within a TSA. At this time, the responsibilities for timber supply analysis and forest health will be obligations for replaceable forest licences and BC Timber Sales (BCTS). It is envisioned that the DFAM participants will prepare a forest health strategy according to standards and methodologies defined in the provincial forest health strategy. In addition, DFAM participants will be required to carry out detection and suppression activities in TSAs where needed to address bark beetle infestations.

Annual surveys to support forest health strategies

The provincial government has the responsibility to conduct an annual aerial survey of the forests of BC and to make these data available to licensees for the development of their DFAM Forest Health Strategy. The aerial surveys are conducted from July through September by regional personnel.

These overviews show the extensive problems such as bark beetle killed forests and current year defoliation. In addition to tabulation of major disturbance factors by region, there are also Annual Summary of Forest Health Conditions in BC reports available at this same web site. These overview surveys must be followed by detailed operational aerial surveys or ground surveys to detail the forest health factors of concern, their abundance and the actions needed at the management level. Certain forest health concerns, particularly diseases such as root diseases, rusts, cankers, decays and dwarf mistletoes are not usually visible during aerial overview surveys, and are detected during detailed ground surveys.

In developing a Defined Forest Area Management strategy in a Timber Supply Area, the following features should be examined:

- Recorded major FHFs in the biogeoclimatic zones and subzones in the area, see Table 4 for a zone overview and Tree Doctor for specific subzone information. These first two items will suggest which FHFs have a history of activity in your area.

- In combination with historical data and the current annual aerial survey, walk-through ground surveys should be made to verify the FHFs present. Experienced foresters will know the major FHF they have to deal with through observations made across the years.
- When carrying out a walk-through survey look carefully for the symptoms that might indicate a FHF. Many of these symptoms and possible causes are summarized in Table 5. Be systematic in your examination of a tree. As you walk towards it you can assess crown foliage condition. As you come closer you will be able to see details of the current state of the branch foliage, the branch tips, the leader and the branches themselves. Careful examination of the trunk and root collar will show whether bark or wood boring insects are active. Cross check the symptoms you find with JP17 or other information sources. Fallen trees, especially recent windfalls, will also give clues about the activities of bark beetles, ambrosia beetles and wood borers (see Table 6 for more information on the latter insects).
- Specific surveys should be carried out where necessary following the guidelines laid down in the Forest Practices Code Guidebooks. These Guidebooks provide a wealth of information on the biological aspects of major significant FHFs as well as the approved methods for surveys and management. You are encouraged to utilize these materials as you develop your management plans. All the FPC Guidebooks are indexed at: www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/guidetoc.htm. Those of particular interest with respect to Forest Health are:

Surveys	*Generic Forest Health Surveys*, Second Edition (2001)
Insects	*Bark Beetle Management* (1995)
	Defoliator Management (1995)
	Management of Terminal Weevils in BC (1996)
Plant Pathogens	*Dwarf Mistletoe Management* (1995)
	Pine Stem Rust Management (1996)
	Root Disease Management (1995)
	Tree Wounding and Decay (1997)

Bark beetle management

The major bark beetles, the mountain pine beetle (IBM), spruce beetle (IBS) and Douglas-fir beetle (IBF) have a significant impact on forestry activities in BC as they kill mature trees. In several areas of BC, a major part of the volume cut is taken from bark beetle infested forests in an attempt to reduce bark beetle populations and utilize the attacked trees before the wood deteriorates on the stump.

Each bark beetle has specific management options that integrate with its life history. IBF and IBS overwinter as adults and emerge in spring. This means that winter-felled trees as well as blow down and snow/ice break trees are vulnerable to attack. All merchantable material should be transported to a sawmill before spring breakup. IBM over winters in the larval stage and does not emerge until late June or early July. Spring sampling determines the degree of over wintering mortality and forewarns summer population levels. The strategy is based on the fundamental elements of the bark beetle-host interactions that are fully described in the FPC Bark Beetle Management Guidebook (www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/beetle/betletoc.htm).

Table 5: Some general symptoms and signs of damage to trees and possible causative forest health factors as seen at ground level.

PART OF TREE	Forest Health Factor		
Observable Symptom/Sign	Insect	Disease	Abiotic or Mammal
WHOLE CROWN FOLIAGE			
Chlorotic, thin, some needle drop, distress cones may be present; also may see sudden reduction in height increment, some trees dead or fallen		Root rot	
Thin, red/brown crown foliage, with some (current) needles green		Fungal diseases of needles: blights, casts	
Needles intact but all foliage red (may also see brown boring dust on main stem, and pitch tubes or resin flow)	Bark beetles		
Top foliage stripped (remaining foliage green)	Caterpillars or sawfly larvae defoliators		
BRANCH FOLIAGE			
Chewing of current foliage only	Budworm caterpillars		
Chewing of all ages of foliage	Caterpillars or sawfly larvae defoliators		
Chlorotic spots on distorted needles with white tufts; on Douglas-fir	Adelgids		
Stunted needles; on larch.	Larch casebearer		
Chlorotic spots on old foliage with yellowing; needle loss; on Sitka spruce	Green spruce aphid		
Red branch flagging; on pines		Blister rusts (cankers) (*Cronartium* spp.)	

Green tip (current year foliage); with one or more bare sections with previous year(s) needles lost, or present and chlorotic/red/ brown (possibly bearing fruiting bodies/ spores); oldest needles still retained		Needle cast	
Current year needles present and green; all previous year(s) needles shed, or present and chlorotic/red/ brown (possibly bearing fruiting bodies/spores)		Needle blight	
Chlorosis and necrosis of needles			Drought
BRANCH TIPS			
Resinosis of bud; on pines	European pine shoot moth		
Flagging of branch tips; on Douglas-fir	Shoot beetle		
Cone-like galling on tip; on spruces	Adelgids		
Reddening of foliage buds; may also see callused patches on trunk and long vertical cracks			Frost kill
LEADERS			
Dying or dead, possibly with stem deformities (crooked and or multiple leaders, crooks, forks)	Terminal weevils:		
on lodgepole pine	Lodgepole terminal weevil		
on spruces	Spruce weevil (= white pine weevil)		
BRANCHES			
Dense brooming (denser than dwarf mistletoes), possibly with dead branches, stem deformity, and/or growth reduction; powdery orange-yellow spores may be present on needles; needles become deciduous (are lost annually)		Rust fungi (spruce broom rust, fir broom rust)	

Table 5 (cont'd.)

PART OF TREE Observable Symptom/Sign	Forest Health Factor Insect	 Disease	 Abiotic or Mammal
Lion's tails; or dense brooms (denser than dwarf mistletoes), possibly with dead branches, stem deformity, and/or growth reduction; infected needles have small dark streaks (fruiting bodies); oldest needles retained		Elytroderma needle cast	
Brooming, sometimes with swellings of branch or main stem, and/or small aerial shoots growing from host, or basal cups present after shoots shed		Dwarf mistletoes	
Canker that is elongate, oval, sunken in centre; fruiting bodies may be present; resinosis		Branch/stem cankers e.g. Dermea canker	
Woody galls on main stem or branches; spore-bearing blisters present on galls in early summer; animal feeding on older cankers followed by resinosis		Branch/stem rusts (cankers) Western gall rust (*Endocronartium harknessii*)	
Canker; blisters bearing spores present on main stem or branches in early summer; animal feeding on older cankers; on pines		Branch/stem rusts (cankers) (*Cronartium* spp.)	
Conk on stems, branches		Heart rot	
MAIN BOLE			
Brown boring dust (frass); pitch tubes or resin flow; green or red foliage: on healthy living trees;	Primary bark beetles:		
on lodgepole pine	Mountain pine beetle		

on stressed living trees;			
on Douglas-fir	Douglas-fir beetle		
on spruces	Spruce beetle		
on subalpine fir (sometimes amabilis fir)	Western balsam bark beetle		
Canker that is elongate, oval, sunken in centre; fruiting bodies may be present; resinosis		Branch/stem cankers e.g. Atropellis canker	
Woody galls on main stem or branches; spore-bearing blisters present on galls in early summer; animal feeding on older cankers followed by resinosis		Branch/stem rusts (cankers) Western gall rust (*Endocronartium harknessii*)	
Canker; blisters bearing spores present on main stem or branches in early summer; animal feeding on older cankers; on pines		Branch/stem rusts (cankers) (*Cronartium* spp.)	
Bark gnawed from trees			American porcupine
Bark stripped from trees			Black bear

FALLEN TREES/SAWLOGS

Brown boring dust (frass); pitch tubes or resin flow; green or red foliage:	Primary bark beetles (listed below) and smaller secondary bark beetles:		
on Douglas-fir (sometimes western larch)	Douglas-fir beetle		
on spruces	Spruce beetle		
on subalpine fir (sometimes amabilis fir)	Western balsam bark beetle		
Fine white boring dust (contains both sawdust and frass); boreholes approximately 1.4 mm in diameter or smaller	Ambrosia beetles		

Table 5 (cont'd.)

PART OF TREE	**Forest Health Factor**		
Observable Symptom/Sign	**Insect**	**Disease**	**Abiotic or Mammal**
Coarse "shredded" white boring dust (contains both sawdust and frass); boreholes	Longhorn wood-boring beetles		
Fruiting bodies on fallen logs		Heart rot	
ROOT COLLAR			
White resinous mixture of duff around root collar	Warren's root collar weevil		
ROOTS			
Rotted roots or lack of laterals; fruiting bodies present ephemerally on roots, stumps, or ground, or absent		Root rot	
Shoestring rhizomorphs and/or white mycelial fans under bark; basal resinosis; mushroom fruiting body		Armillaria root disease (*Armillaria ostoyae*)	
Openings in mature stands; pitted, laminar decay with red-brown stain and hair-like hyphae; ectotrophic mycelium on roots in mineral soil		Laminated root rot (*Phellinus weirii*)	
Small openings with cris-crossed windthrown trees; advanced pitted decay present in broken roots; wood remains firm; fruiting body (mushroom-like with porous underside) present in late summer		Tomentosus root rot (*Inonotus tomentosus*)	
WOOD STAINS/DECAY			
Blue stain	Bark beetle-vectored symbiotic fungus		
Black stain, with small bore holes and fine white boring dust	Ambrosia beetle-vectored symbiotic fungus		

Streaked black stain in sapwood		Black stain root disease (*Leptographium wageneri*)	
Solid black stain in sapwood		Atropellis canker	
Decayed wood is typically brown, crumbly, in small cubes		Brown rot	
Decayed wood may appear white, spongy, stringy, and/or laminar; may eventually decay completely		White rot	
SEEDLINGS			
Foliage chewed	Cutworms		
Shoots red, bark stripped from roots or root collar	Root collar weevils, crane-fly larvae (leatherjackets)		
Terminal and lateral shoots are "clipped"; girdling on root collar and roots			Rabbits/hares or voles
SEED AND CONE			
Cones turn brown prematurely and bear orange spores on scales; on spruces		Spruce cone diseases (*Chrysomyxa* spp.)	
Frass on cones	Caterpillars		
Galling of seed	Cone midge larvae (*Contarinia* spp.)		
Abnormal seeds (as visualized by x-ray)	Seed chalcid (*Megastigmus* spp.) leaf-footed bugs (*Leptoglossus occidentalis*)		

Table 6: Characterizing features of wood damaging insects: ambrosia beetles, longhorned borers and flatheaded borers. These 3 families are all beetles (Order Coleoptera).

Wood boring beetle family	**Ambrosia beetles (Scolytidae)**	**Longhorned (roundheaded) wood boring beetles (Cerambycidae)**	**Flatheaded (metallic) wood boring beetles (Buprestidae)**
Economically important examples	– Striped ambrosia beetle *Trypodendron lineatum* – Scratch-faced ambrosia beetle *Gnathotrichus sulcatus* (Hosts: both beetles attack most conifer spp.)	Sawyer beetle *Monochamus* spp. (Hosts: pines, spruces, firs, Fd) [*Monochamus* spp. vector the pine-wood nematode *Bursaphelenchus xylophilus* in the US, Japan, China and other parts of the world.]	– Western redcedar borer *Trachykele blondeli* ISB (Host: Cw) – Golden buprestid *Buprestis aurulenta* (Hosts: Fd, Py) – Flatheaded fir borer *Melanophila drummondi* (Hosts: Fd, firs, spruces, Hw, Lw)
Damage	Attack dead trees, winter-felled logs, logs left on dry land, and the upper parts of logs in booms; tunnel in sapwood; introduce black-staining "ambrosia" fungi	Bore weakened trees, windthrows, logs, dead and dying material	Bore weakened trees, windthrows, logs, dead and dying material
Distinguishing features of larva	Feed in small closed niches	Rounded thoracic region	Flattened thoracic region
Distinguishing features of adult	Feed on ambrosia fungi in main gallery	Long antennae	Flattened shape; often metallic colour
Gallery	Boring produces fine white-coloured frass at entrance hole; galleries cross grain in sapwood and fungal stain is a major agent of visual degrade	Loosely packed with fibrous frass and elliptical in cross-section	Tightly packed with frass; flattened (parallel-sided) oval in cross-section
Adult exit hole	Entrance/exit hole is circular (diameter = 1.4 mm for *T. lineatum*; 1.2 mm for *G. sulcatus*)	Circular	Elliptical

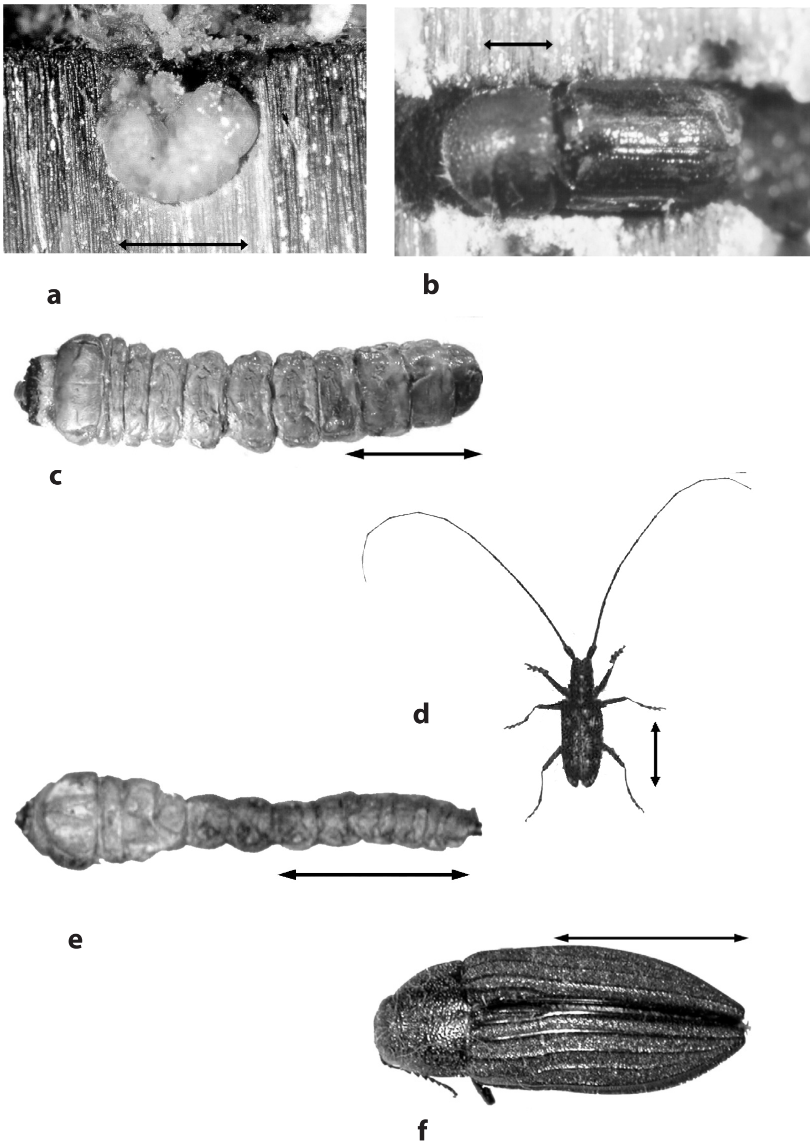

Figure 2:
Wood boring beetles described in Table 6 – *Trypodendron lineatum*, an ambrosia beetle of family Scolytidae (a) larva in feeding niche and (b) adult; *Monochamus* spp., a longhorned beetle of family Cerambycidae (c) larva and (d) adult; *Buprestis aurulenta*, a flat headed wood borer of family Buprestidae (e) larva and (f) adult. For figures (a) and (b) the scale bar indicates 1 mm; for (c) – (f) the scale bar indicates 1 cm.

Young stands are relatively immune from successful bark beetle attack but as the stands age, especially after about 80 years (16-20 cm diameter) their phloem is thick enough to support a successful bark beetle attack. Preventive management recognizes that older trees are more susceptible so that there is a need to plan timely harvesting of these most susceptible stands. Hazard rating systems relate tree and site characteristics to attack success by beetles. Over time, large expanses of even-aged forests can be converted to a mosaic of age classes and tree species. It is also possible to space lodgepole pine stands to 4 m or 5 m spacing so that trees retain sufficient vigour to successfully ward off an IBM attack. Such stand manipulation needs to be incorporated into forest health strategic plans.

There are various ways to directly control beetle populations. While they are at low levels, spots of newly attacked trees can be harvested, felled and burned or injected with MSMA. When spots amalgamate into patches then pheromone baits can be used to attract beetles into a stand during the summer so long as the whole stand is harvested over the winter and the infested trees transported to a mill for manufacture. When a very large area of mature forest is infested by beetles, the only option is to salvage log the better quality stands and utilize the fibre before it deteriorates on the stump. In isolated areas, it may not be possible to carry out any management at all and these trees will deteriorate and natural stand succession will take place.

The key elements of bark beetle management (listed in the Provincial Bark Beetle Strategy) are:

- Rating stands for susceptibility and risk of depletion
- Annual detection surveys and mapping of infestations
- Annual assessments of rates of change in infestation levels and spread
- Prompt, appropriate and thorough action on all infestations where suppression or control to some degree is feasible.

All management plans need to allow for this potentially serious impact on planning objectives and to ensure continued management actions protect investment both in the local licence area and in adjacent jurisdictions.

Use of pesticides

There are occasions when you might need to intervene directly by using a pesticide. All pesticides must be used in a manner that meets federal and provincial regulations, especially the BC *Pesticide Control Act* and its regulations (available at www.qp.gov.bc.ca/statreg/reg/P/319_81.htm#section%2028). All pesticides must be used only as indicated on the label of the pesticide container, both by method of application as well as only for listed approved target organisms. If your target FHF is not listed on the label then that product cannot be used. People planning to use a pesticide on public lands need to have a Pesticide Use Permit or have an approved Pest Management Plan. Pesticide Use Permits are issued by the Ministry of Water, Lands, Air and Parks. The person carrying out the application needs to have a Pesticide Applicator's Certificate.

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Additional internet resources

BC Ministry of Forests:

Forest Practices Branch – Home: www.for.gov.bc.ca/hfp/hfp.htm

Forest Range and Practices Act: www.for.gov.bc.ca/code/

Legislation & Regulations pertaining to forestry: www.for.gov.bc.ca/tasb/legsregs/comptoc.htm

General

A listing of Forest Pathology related websites:

www.umaine.edu/fes/Classes/int256/home/web_sites.htm

USDA Forest Service- Forest Health Protection website: www.fs.fed.us/foresthealth/

USDA Forest Service Pacific Northwest Region Office: www.fs.fed.us/r6/nr/fid/

Glossary

The following are common or important forest health terms that may have been used in this chapter or that are useful to be aware of. For a full glossary of Forest Health terminology (PesTerms) see Doliner and Borden (1984).

Abiotic Non-living.

Basal resinosis (pitching) Large exudations of pitch at the base of the stem at or below the root collar, often associated with Armillaria root disease or Warren's root collar weevil. See also **resinosis**.

Broom/brooming In woody plants, an abnormal shortening of internodes (the region of stem between any two nodes, the places where leaves attach) and proliferation of weak shoots, forming a dense brush-like mass (also called a **witches' broom**). Commonly induced by dwarf mistletoes, rust fungi, or other organisms, but sometimes a response to abiotic stresses. Mistletoe brooms are evergreen, while needles of brooms induced by rusts generally last only one year.

Canker A localized, well-delineated area of diseased tissue in bark and cambium of main root, stem, or branch, often with an overgrowth of surrounding tissues as a result of reaction of the host plant to infection.

Chlorosis Yellowing of normally green tissue, due to destruction or reduced production of chlorophyll, often a symptom of some metabolic deficiency, disease, feeding by sucking insects, root or stem girdling, or extremely reduced light. A distinction is sometimes drawn between **chlorosis** and lack of colour due to growth under insufficient light (**etiolation**).

Crook A defect in trees or logs, consisting of an abrupt bend, that can result from insect-induced topkill and recovery by a lateral branch. A minor crook is called a **crease**. See also **fork**, **shepherd's crook,** and **staghead**.

Damage The physical and ecological effects of a forest health factor on tree or forest growth, structure, productivity, and/or use.

Decay The decomposition of wood caused by fungi, resulting in softening, progressive loss of strength and weight, and often changes in texture and colour. See also **laminar decay** and **rot**.

Dieback The gradual and progressive dying, starting at the tips, of shoots, twigs, tops, branches or roots.

Duff The organic litter layer of the forest floor comprised of organic debris such as leaf litter, bark fragments, twigs, etc. in varying states of decomposition.

Flagging A conspicuous, red or chlorotic branch in a green crown.

Fork A major defect resulting when two laterals assume dominance, possibly caused by loss of a leader or apical shoot due to terminal weevils. See also **crook**, **shepherd's crook,** and **staghead**.

Frass Solid excrement of insects, particularly larvae; that of wood-eating insects such as bark beetles can be called **boring dust**.

Frequency The number of repetitions of a periodic process (e.g. defoliator outbreak) in a period of time (e.g. in a 25-year period). A relatively high frequency would be an outbreak every decade.

Fungal anatomical structures:

> **Conk** The shelf-like or flat spore-producing structure of some wood decay fungi, particularly heart rot fungi; forms on the external surface of its host; seen on tree trunks, branches or stumps.
>
> **Ectotrophic mycelium** A mass of white or gray mycelium found on the outside surface of roots; the mycelium may be covered by a dark brown crust if it has been exposed to the air. Ectotrophic mycelium facilitates the initial spread of *Phellinus weirii* from root to root. See also **mycelium**.
>
> **Fruiting body** Fungal structures that contain or bear spores, such as mushrooms and **conks**.
>
> **Hypha (plural hyphae)** A microscopic, fine, thread-like, often branched structure formed of fungal cells.
>
> **Mycelial fans** Fan-shaped mass of hyphae, formed between bark layers or between bark and wood of trees. Often found near the base of trees infected with Armillaria root rot.
>
> **Mycelial sheet** A felt of hyphae, in other than a fan-shaped pattern, formed in cracks in decayed wood, or between bark layers or between bark and wood of trees.
>
> **Mycelium** A mass of vegetative, interwoven hyphae, usually considered as distinct from the fruiting body. See also **ectotrophic mycelium**.
>
> **Rhizomorph** A root-like strand composed of hyphae, often much branched, occurring in certain fungi, e.g. *Armillaria*.

Gallery A passage, burrow, tunnel or mine excavated by an insect (especially by bark beetles) in plant tissues for feeding, oviposition, or shelter. Bark beetle galleries are constructed in the inner bark and often may etch the surface of the wood. Their general pattern is characteristic for particular genera and even for certain species.

Galls/galling A localized proliferation of greatly modified plant tissue, induced by another organism such as an insect or disease fungus, that results in a pronounced permanent swelling, lump, or abnormal outgrowth of malformed bark or woody material. Commonly has a characteristic shape, often spherical, unlike any organ of the normal plant.

Girdling The destruction of the conducting bark tissues (phloem) all the way around a trunk, stem, branch or root, preventing the movement of photosynthetic products and causing the affected plant part to die. When the trunk is girdled, nutrient depletion may cause the roots to die, cutting off the water supply to the crown, thus killing the top as well. Many deciduous trees once girdled can repair the damage and survive. Girdling may be caused by bark beetles, weevils, rodent gnawing, or fungal infections.

Gouting Excessive swelling of a branch or shoot, often accompanied by misshapen needles and buds; frequently caused by balsam woolly adelgid on true firs.

Incidence The proportion or percentage or frequency of occurrences of a given phenomenon, such as a disease or insect infestation, in a defined sampling unit (normally a plot or a stand). To avoid confusion when using incidence, always indicate the sampling entity and sampling unit.

Laminar decay Decayed wood separating readily along growth rings (= delamination), characteristic of infection by *Phellinus weirii*.

Lion's tail The isolated tuft of current needles remaining on branches or branchlets after all the other needles have been cast as the result of a severe foliage disease.

Necrosis The death or disintegration of cells or tissues while they are still part of a living organism; in plants usually resulting in a darkening of the affected tissue.

Parasite An organism that lives part or all of its life cycle in (**endoparasite**) or on (**ectoparasite**) a different organism, the host, and from which it derives part or all of its sustainance. See also **parasitoid**.

Parasitoid A parasite, typically an endoparasitic fly larva or wasp larva, that ultimately kills its host, often by consuming most or all of its internal tissues. See also **parasite**.

Pathogen Organisms (usually very small or microscopic) such as bacteria, fungi, protozoa, helminths, viruses, or viroids, that cause or induce disease in their host.

Pitch tube A mass of resin and often frass or boring dust at the point of entry of an insect (often a bark beetle) into bark, cones etc. of various conifers, as a result of the severing of resin ducts by the boring activity of the insect.

Primary bark beetles A bark beetle that is the first to arrive at, utilize, complete development in, and/or kill an apparently healthy, living tree. See also **secondary bark beetles**.

Resinosis Flow of resin or pitch in a conifer, in response to infection, wounding or insect (often bark beetle) attack. See also **basal resinosis**.

Root collar The part of a tree where the main roots join the trunk, usually at or near ground level.

Rot A state of (usually advanced and obvious) decay caused by fungi. The word **rot** also refers to or is part of the name of a disease characterized by this symptom. See also **decay**.

Saprophyte An organism that commonly feeds on dead organic material, usually by decomposing and absorbing it, and assisting in its decay. Saphrophytes, in certain circumstances, may attack living hosts (e.g. those weakened by primary pathogens or stress) and become pathogens.

Secondary bark beetles A bark beetle that attacks trees that are already weakened, dying or dead as a result of a primary insect (often a primary bark beetle) or pathogen.

Shepherd's crook A leader or branch with a down-curved tip in the shape of a shepherd's crook, characteristic of attack by certain insects (especially terminal weevils on spruces) or pathogens (for example, Fusarium root rot in Douglas-fir seedlings). See also **crook, fork,** and **staghead**.

Sign Objective evidence, such as the visible portion of a pathogen, or its products, seen on or in the host. Compare with **symptom**.

Staghead Three or more laterals assuming dominance; a major defect often resulting from terminal weevil attack. See also **crook, fork**, and **shepherd's crook**.

Symptom A phenomena, or circumstance observed or detected in the host that is associated with, or a known reaction to, disease, infection, injury, or attack. Compare with **sign**.

Forest Measurements

BIOMETRICS
Useful definitions and formulae in statistics

by

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BIOMETRICS

Useful definitions and formulae in statistics

A population consists of the totality of the observations with which we are concerned.

A sample is a subset (portion) of the population.

Descriptive statistics: The phase of statistics which seeks only to describe and analyze a given set of observations without drawing any conclusions about a larger set of observations (population) is called descriptive or deductive statistics.

Statistical inference: If a sample is representative of a population, important conclusions about the population can often be inferred from analysis of the sample. The phase of statistics dealing with conditions under which such inference is valid is called inductive statistics or statistical inference.

Descriptive Statistics

Variable: Is an observable characteristic associated with an individual and differing among individuals. **Observations** (**data**) are specific values of a variable.

Raw data: Unorganized sets of numbers (observations).

Frequency distribution: The overall range of the observed values are divided into classes, and the numbers of observations that fall into each class are counted.

The following terms are used in relation to frequency distributions (or grouped data).

Class limits are the greatest and the least possible observations in a given class.

Class boundaries are values dividing the total range of the observed values so as to permit the assignment of every value to a particular class. Consequently, they must be values that are impossible as observations, and they are half way between the upper class limit of the j-th class and the lower class limit of $(j + 1)$-th class.

Class range or width is the difference between the class boundaries of a given frequency class.

Class mark or midpoint is at the centre of the class interval (half way between the upper and lower class boundaries of a given class).

Frequency is the number of observations in any class.

Relative frequencies are the class frequencies divided by the total number of observations (multiply by 100 if percentage relative frequencies are desired).

Histograms (or bar charts) and frequency **polygons** are graphic representations of a frequency distribution.

Measures of central tendency

Mean or arithmetic average: for a given set of *n* observations, the mean is the sum of the observations divided by *n*.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{x_1 + x_2 + \ldots + x_n}{n}$$

where: n = number of observations in the sample
x_i = *i*-th observation
$\bar{x}$ = sample mean

For a population:

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N} = \frac{x_1 + x_2 + \ldots + x_N}{N}$$

where: N = number of observations in the population
x_i = *i*-th observation
μ = population mean

For grouped data:

$$\bar{x} = \frac{\sum_{j=1}^{c} f_j m_j}{\sum_{j=1}^{c} f_j} = \frac{f_1 m_1 + f_2 m_2 + \ldots + f_c m_c}{f_1 + f_2 + \ldots + f_c}$$

where: c = number of frequency classes
m_j = class midpoints
f_j = class frequencies

$$\sum_{j=1}^{c} f_j = n$$

The **median** is a number such that half of the observations are less than that number and half of the observations are greater than that number.

The **mode** is that observation which occurs most frequently. A set of observations can have more than one mode.

Measures of variation (spread)

The **range** is the difference between the largest (maximum) and the smallest (minimum) observations.

Mean deviation

$$MD = \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{n}$$

where: n = number of observations in the sample
x_i = *i*-th observation
$\bar{x}$ = sample mean

Standard Deviation

For a sample: $$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n - 1}} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n - 1}}$$

where: s = sample standard deviation.

$$\sum_{i=1}^{n} x_i^2 = x_1^2 + x_2^2 .. x_n^2 = \text{ uncorrected sum of squares,}$$

$$\sum_{i=1}^{n} x_i = x_1 + x_2 .. x_n$$

For a sample when the population mean (μ) is known: $$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}}$$

For a population: $$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N}}$$

where:
s = sample standard deviation
σ = population standard deviation
n = number of observations in the sample
x_i = i-th observation
N = number of observations in the population
$\overline{x}$ = sample mean
μ = population mean

For grouped data: $$s = \sqrt{\frac{\sum_{j=1}^{c} f_j (m_j - \overline{x})^2}{n - 1}} = \sqrt{\frac{\sum_{j=1}^{c} f_j m_j^2 - \left(\sum_{j=1}^{c} f_j m_j\right)^2 \Big/ n}{n - 1}}$$

where:
s = sample standard deviation
c = number of frequency classes
m_j = class midpoints
f_j = class frequencies

$$\sum_{j=1}^{c} f_j = n$$

Variance
For a sample is s^2.
For a population is σ^2.
Coefficient of variation is the sample standard deviation expressed as a percent of the sample mean: $CV = \frac{100s}{\overline{x}}$

Note, as $\overline{x} \rightarrow 0$, $CV \rightarrow \infty$ for the same standard deviation or spread.

Theoretical Distributions

Some discrete probability distributions

Uniform distribution: If a random variable X assumes the values of $x_1, x_2 \ldots x_k$, with equal probability, then the discrete uniform distribution is given as:

$$f(x;k) = \tfrac{1}{k}, \quad \text{for } x = x_1, x_2, \cdots x_k$$

where: $x = x_1, x_2 \ldots x_k$

$f(x; k)$ = probability of x, given k

Binomial distribution: If a random experiment can result in a success with probability p, and a failure with probability $q = 1 - p$, then the probability distribution of the binomial random variable X, the number of successes in n independent trials, is:

$$f(x;n,p) = \binom{n}{x} p^x q^{n-x} = \frac{n!}{x!(n-x)!} p^x q^{n-x}, \qquad \text{for } x = 0,1,2 \ldots n$$

where: $x = 0, 1, 2 \ldots n$

$f(x; n,p)$ = probability of x, given n and p

restriction: p remains constant from trial to trial and the n trials are independent.

Hypergeometric distribution: If a finite population of size N contains k items labelled "success" and $N - k$ items labelled "failure", then the probability distribution of the hypergeometric random variable X, the number of successes in a random sample, taken without replacement, of size n, is:

$$f(x;N,n,k,) = \frac{\binom{k}{x}\binom{N-k}{n-x}}{\binom{N}{n}} = \frac{\dfrac{k!}{x!(n-k)!} \dfrac{(N-k)!}{(n-x)!\,[(N-k)-(n-x)]!}}{\dfrac{N!}{n!(N-n)!}}$$

where: $x = 0, 1, 2 \ldots n$

$f(x; N,n,k)$ = probability of x, given N, n and k

Geometric distribution: If a random experiment can result in a success with probability p (p is constant from trial to trial) and a failure with probability $q = 1 - p$, then the probability distribution of the random variable X, the number of the trial on which the first success occurs, is:

$$f(x; p) = pq^{(x-1)} \qquad \text{for } x = 1, 2, 3, \ldots\ldots$$

where: $f(x; p)$ = probability of x, given p

Negative binomial distribution: If a random experiment can result in a success with probability p (p is constant from trial to trial) and a failure with probability $q = 1 - p$, then the probability distribution of the random variable X, the number of the trial on which the k-th success occurs, is:

$$f(x;p) = pq^{(x-1)} = \frac{(x-1)!}{(k-1)!\left[(x-1)-(k-1)\right]!} p^k q^{x-k}$$

where: $f(x; k, p)$ = probability of x, given k and p

Poisson distribution: The probability distribution of the Poisson random variable X, representing the number of successes occurring in a given time interval or specified regions, is:

$$f(x;\mu) = \frac{e^{-\mu}\mu^x}{x!}, \quad \text{for } x = 0, 1, 2, 3, \ldots..,$$

where: $f(x; \mu)$ = probability of x, given μ

μ = average number of successes occurring in the given time interval or specified region

e = 2.71828

Continuous distributions

Normal distribution: If X is a normal random variable with mean μ and variance σ^2, then the probability density function of the normal curve is:

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, \qquad \text{for } -\infty < x < \infty,$$

where: π = 3.14159

e = 1.71828

To obtain probabilities for x being between "a" and "b" use the Z-table (probabilities for standardized normal distribution).

Sampling Distributions

The probability distribution of a statistic (e.g. sample mean) is called a sampling distribution. The standard deviation of a sampling distribution of a statistic is called the "standard error" of the statistic (e.g. standard error of the mean).

Sampling distribution of the mean: If all possible random samples of size n are drawn with replacement from a finite population of size N (or from an infinite population with or without replacement), with mean μ and standard deviation σ, then the sampling distribution of the mean $\bar{x}$ will be approximately *normally* distributed with a mean $\mu_{\bar{x}} = \mu$ and a standard deviation (standard error of the mean), $\sigma_{\bar{x}} = \sigma/\sqrt{n}$. Hence the transformation:

$$z_i = \frac{\bar{x}_i - \mu}{\sigma_{\bar{X}}}$$ can be used to obtain probabilities for $\bar{x}$.

If the samples of size n are drawn without replacement from a finite population of size N, the standard error of the mean is:

$$\sigma_{\overline{\overline{X}}} = \frac{\sigma}{\sqrt{n}}\sqrt{\frac{N-n}{N-1}}$$

where: $\sqrt{\frac{N-n}{N-1}}$ = finite population correction factor.

If the population variance σ, is unknown, $t_{i(\nu)} = \frac{\bar{x}_i - \mu}{s/\sqrt{n}}$

where: $s_{\bar{x}} = \frac{s}{\sqrt{n}}$ is the standard error of the mean, based on the sample variance.

ν = degrees of freedom = $n - 1$.

the *"t"* distribution with $n - 1$ degrees of freedom provides probabilities about the sample mean $\bar{x}$.

Sampling distribution of the variance: If s^2 is the variance of a random sample of size n taken from a normal population having the variance σ^2, then the transformation to a chi-square distribution with $n - 1$ degrees of freedom will provide probabilities for s^2.

$$\chi^2_{i(n-1)} = \frac{(n-1)s_i^2}{\sigma^2}$$

If σ_1^2 and σ_2^2 are the variances of independent random samples of sizes n_1 and n_2 taken from two normal populations with variances σ_1^2 and σ_2^2 respectively, then the transformation to an F distribution with $n_1 - 1$ and $n_2 - 1$ degrees of freedom will provide probabilities about the ratio $\left(s_1^2/s_2^2\right)$ of the two variances.

$$f_{i(\nu_1,\nu_2)} = \frac{s_1^2/\sigma_1^2}{s_2^2/\sigma_2^2} = \frac{s_1^2\sigma_2^2}{s_2^2\sigma_1^2}$$

where: ν_1 = degrees of freedom of s_1^2

ν_2 = degrees of freedom of s_2^2

Statistical Inference

Confidence (or fiducial) limits:
The probability that a confidence interval will enclose the estimated parameter is called the confidence coefficient. Usual values for the confidence coefficient are 0.90, 0.95 and 0.99.

The lower point of the confidence interval is called the lower confidence limit and the upper point of the interval is called the upper confidence limit.

Formulae given here are for cases when the population variance is unknown. Consult references for other cases.

Estimating the mean:

$$P\left(\bar{x} - t_{\alpha/2(n-1)}\frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2(n-1)}\frac{s}{\sqrt{n}}\right) = 1 - \alpha$$

where:
$\bar{x}$ = sample mean
s = sample standard deviation
n = sample size
$t_{\alpha/2(n-1)}$ = value of the t distribution with $n - 1$ degrees of freedom with $\alpha/2$ probability
$1 - \alpha$ = confidence coefficient
μ = unknown population mean

Estimating the difference between two means:

$$P\left[(\bar{x}_1 - \bar{x}_2) - t_{\alpha/2(v)} s_{\bar{X}_1 - \bar{X}_2} < \mu_1 - \mu_2 < (\bar{x}_1 - \bar{x}_2) + t_{\alpha/2(v)} s_{\bar{X}_1 - \bar{X}_2}\right] = 1 - \alpha$$

For the use of the formula above, we distinguish between three cases when the two population variances are unknown. For each case the standard error of the differ-ences of two means and the degrees of freedom are calculated differently.

Case 1: Both n_1 and $n_2 \geq 30$ (large samples).

$$s_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$$

and $\nu = \infty$

Case 2: n_1 or n_2 or both < 30 (small samples) and it is assumed that $\sigma_1^2 = \sigma_2^2$

$$s_{\bar{X}_1 - \bar{X}_2} = s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

where: $$s_p = \sqrt{\frac{s_1^2(n_1 - 1) + s_2^2(n_2 - 1)}{n_1 + n_2 - 2}}$$

and $\nu = n_1 + n_2 - 2$

Case 3: n_1 or n_2 or both < 30 (small samples) and it is assumed that $\sigma_1^2 \neq \sigma_2^2$

$$s_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$$

and (a)

$$\nu = \frac{\left[\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right]^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(s_2^2/n_2\right)^2}{n_2 - 1}}$$

or (b) ν = smaller of $n_1 - 1$ or $n_2 - 1$.

(a) is the more precise alternative, however, (b) suffices for most practical applications.

where: $\bar{x}_1, \bar{x}_2$ = sample means
μ_1, μ_2 = unknown population means
n_1, n_2 = number of observations in the two samples
$1 - \alpha$ = confidence coefficient
s_p = pooled standard deviation
s_1^2, s_2^2 = sample variances

Estimating a proportion:

$$P\left[\hat{p} - z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}} < p < \hat{p} + z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}}\right] = 1 - \alpha$$

where:

$\hat{p}$ = sample proportion
$\hat{q}$ = $1 - \hat{p}$
n = sample size
$z_{\alpha/2}$ = value of the Z distribution with $\alpha/2$ probability (use t value if $n < 30$, with $n - 1$ degrees of freedom)
$1 - \alpha$ = confidence coefficient
p = unknown population proportion

Estimating the difference between two proportions:

$$P\left[(\hat{p}_1 - \hat{p}_2) - z_{\alpha/2}s_{\hat{P}_1-\hat{P}_2} < p_1 - p_2 < (\hat{p}_1 - \hat{p}_2) + z_{\alpha/2}s_{\hat{P}_1-\hat{P}_2}\right] = 1 - \alpha$$

where: $s_{\hat{P}_1-\hat{P}_2} = \sqrt{\hat{p}_c\hat{q}_c\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$, $\hat{p}_c = \dfrac{n_1\hat{p}_1 + n_2\hat{p}_2}{n_1 + n_2}$ and $\hat{q}_c = 1.0 - \hat{p}_c$.

Estimating the variance:

$$P\left[\frac{(n-1)s^2}{\chi^2_{\alpha/2\,(n-1)}} < \sigma^2 < \frac{(n-1)s^2}{\chi^2_{1-\alpha/2\,(n-1)}}\right] = 1 - \alpha$$

where: s^2 = sample variance
$\chi^2_{\alpha/2}, \chi^2_{1-\alpha/2}$ = sample size
= values of the chi-square distribution with $n - 1$ degrees of freedom with $\alpha/2$ and $1 - \alpha/2$ probability
$1 - \alpha$ = confidence coefficient
σ^2 = unknown population variance

Estimating the ratio of two variances:

$$P\left[\frac{s_1^2}{s_2^2}\frac{1}{F_{\alpha/2(v_1,v_2)}} < \frac{\sigma_1^2}{\sigma_2^2} < \frac{s_1^2}{s_2^2}F_{\alpha/2(v_2,v_1)}\right] = 1-\alpha$$

where: s_1^2, s_2^2 = sample variances
ν_1 = $n_1 - 1$; $\nu_2 = n_2 - 1$, degrees of freedom
n_1, n_2 = sample sizes
$F_{\alpha/2}(\nu_1, \nu_2)$ = value of the F distribution with ν_1 and ν_2 degrees of freedom with $\alpha/2$ probability
$F_{\alpha/2}(\nu_2, \nu_1)$ = value of the F distribution with ν_2 and ν_1 degrees of freedom with $\alpha/2$ probability
$1 - \alpha$ = confidence coefficient
σ_1^2, σ_2^2 = unknown population variances

Test of Hypotheses

A statistical hypothesis is an assumption or statement, which may or may not be true, concerning one or more populations. Test of hypothesis is a procedure for determining whether sample results support a hypothesis about a population parameter value or whether the sample results indicate that a hypothesis should be rejected. Several tests of hypotheses are tested in the following text. They share certain features with the example below, and their analysis can conveniently be set out in a standard sequence of steps, as indicated in the following example:

Test concerning a mean against a hypothetical constant:

1. Formulate the null hypothesis H_0 in statistical terms: H_0: $\mu = \mu_0$

   where: μ_0 is a constant value
   μ is the unknown population mean

   For example: H_0: $\mu = 45$ The assumption (hypothesis) here is that the average dbh of a population is 45 cm.

2. Formulate the alternative hypothesis H_1 in statistical terms: It can be in three different forms.

   H_1: $\mu \neq \mu^0$ Two-tail test
   or H_1: $\mu < \mu^0$ One-tail test
   or H_1: $\mu > \mu^0$ One-tail test

   Only one of these alternatives can be stated in any given analysis. For example: H_1: $\mu \neq \mu^0$.

   In order to use one of the alternatives for one-tail test ($\mu < 45$ or $\mu > 45$), some additional information is required, that is, it has to be suspected that the average dbh of the given stand should be, for some reason, greater than 45.

3. Set level of significance, α. Usually 0.1, 0.05 or 0.01 is used. For example: $\alpha = 0.05$.

4. Collect data and calculate the mean and standard deviation. Let us say that for the example, 20 observations ($n = 20$) were collected and the average dbh was 37.6 cm with a standard deviation (s) of 10.2 cm.

   $n = 20$; $\bar{x} = 37.6$ $s = 10.2$

5. Select critical values to define the rejection and acceptance region.

$$t_{\text{crictical}(19)} = -2.093 \text{ and } 2.093 \quad \text{(two-tail test)}$$

Note that for a two-tail test, we have two critical values, because (0.05) is split into halves and applied at the two tails of t distribution to define the rejection region. For a one-tail test, there is only one critical value since, α as a whole is put either in the upper ($\mu > \mu_0$) or the lower ($\mu < \mu_0$) tail of the distribution to define the rejection region.

6. Calculate the test statistic: $T = \dfrac{\bar{x} - \mu_0}{s/\sqrt{n}} = \dfrac{37.6 - 45.0}{10.2/\sqrt{20}} = -3.24$

Depending on the test, different formulae are used to calculate test statistics.

7. Make decision: For the given example, H_0 is rejected, that is, the unknown population mean is significantly different (smaller) than 45 cm.

If the test statistic would have been within the critical values, –2.093 and 2.093 for this example, H_0 is not rejected.

The following table summarizes the most commonly used statistical tests:

H_0	Test Statistic	H_1	Critical Region
Tests concerning means:			
$\mu = \mu_0$	$T = \dfrac{\bar{x} - c}{s/\sqrt{n}}$	$\mu < \mu_0$ $\mu < \mu_0$ $\mu \neq \mu_0$	$T < -t_\alpha$ $T > t_\alpha$ $T < -t_{\alpha/2}$ $T > t_{\alpha/2}$
$\mu_1 - \mu_2 = d_0$	$T = \dfrac{(\bar{x}_1 - \bar{x}_2) - c}{s_{\bar{X}_1 - \bar{X}_2}}$	$\mu_1 - \mu_2 < d_0$ $\mu_1 - \mu_2 > d_0$ $\mu_1 - \mu_2 \neq d_0$	$T < -t_\alpha$ $T > t_\alpha$ $T < t_{\alpha/2}$ $T > t_{\alpha/2}$

There are three cases for the above test.

Case 1: Both n_1 and $n_2 \geq 30$ (large samples).

$$s_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad \text{and } \nu = \infty$$

Case 2: n_1 or n_2 or both < 30 (small samples) and it is assumed that $\sigma_1^2 = \sigma_2^2$

$$s_{\bar{X}_1 - \bar{X}_2} = s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

where: $$s_p = \sqrt{\frac{s_1^2(n_1-1)+s_2^2(n_2-1)}{n_1+n_2-2}}$$

and $v = n_1 + n_2 - 2$

Case 3: n_1 or n_2 or both < 30 (small samples) and it is assumed that $\sigma_1^2 \neq \sigma_2^2$

where: $$s_{\bar{X}_1-\bar{X}_2} = \sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}$$

and $$\nu = \frac{\left[\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}\right]^2}{\dfrac{\left(s_1^2/n_1\right)^2}{n_1-1} + \dfrac{\left(s_2^2/n_2\right)^2}{n_2-1}}$$

or ν = smaller of $n_1 - 1$ or $n_2 - 1$.

$\mu_D = d_0$ paired observations $\nu = n-1$	$T = \dfrac{\bar{D} - d_0}{s_d/\sqrt{n}}$	$\mu_D < d_0$	$T < -t_\alpha$
		$\mu_D > d_0$	$T > t_\alpha$
		$\mu_D \neq d_0$	$T < -t_{\alpha/2}$
			$T > t_{\alpha/2}$

Tests concerning variances:

$\sigma^2 = \sigma_0^2$ $\nu = n - 1$	$\chi^2_{(n-1)} = \dfrac{(n-1)s^2}{\sigma_0^2}$	$\sigma^2 < \sigma_0^2$	$x^2 < x^2_{1-\alpha}$
		$\sigma^2 > \sigma_0^2$	$x^2 > x^2_\alpha$
		$\sigma^2 \neq \sigma_0^2$	$x^2 > x^2_{\alpha/2}$
			$x^2 < x^2_{1-\alpha/2}$

$\sigma_1^2 = \sigma_2^2$ $v_1 = n_1 - 1$ $v_2 = n_2 - 1$	$F_{(v_1-1, v_2-1)} = \dfrac{s_1^2}{s_2^2}$	$\sigma_1^2 < \sigma_2^2$	$F < f_{1-\alpha(v_1,v_2)}$
		$\sigma_1^2 > \sigma_2^2$	$F > f_{\alpha(v_1,v_2)}$
		$\sigma_1^2 \neq \sigma_2^2$	$F < f_{1-\alpha/2(v_1,v_2)}$
			$F > f_{\alpha/2(v_1,v_2)}$

Tests concerning proportions:

$p = p_0$	$Z = \dfrac{\hat{p} - p_0}{\sqrt{\dfrac{\hat{p}\hat{q}}{n}}}$	$p < p_0$	$Z < -Z_\alpha$
		$p > p_0$	$Z > Z_\alpha$
		$p \neq p_0$	$Z < -Z_{\alpha/2}$
			$Z > Z_{\alpha/2}$

$p_1 - p_2 = d_0$

$$Z = \frac{(\hat{p}_1 - \hat{p}_2) - d_0}{S_{\hat{p}_1 - \hat{p}_2}}$$

$p_1 - p_2 < d_0$	$Z < -Z_\alpha$
$p_1 - p_2 > d_0$	$Z > Z_\alpha$
$p_1 - p_2 \neq d_0$	$Z < -Z_{\alpha/2}$
	$Z > Z_{\alpha/2}$

where: $S_{\hat{p}_1 - \hat{p}_2} = \sqrt{\hat{p}_c \hat{q}_c \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$ and

$\hat{p}_c = \dfrac{n_1 \hat{p}_1 + n_2 \hat{p}_2}{n_1 + n_2}$ and $\hat{q}_c = 1 - \hat{p}_c$; $\hat{p}_c$ = pooled or combined proportion,

or $S_{\hat{p}_1 - \hat{p}_2} = \sqrt{\dfrac{\hat{p}_1 \hat{q}_1}{n_1} + \dfrac{\hat{p}_2 \hat{q}_2}{n_2}}$

where:

μ, μ_1, μ_2 = unknown population means

μ_0 = hypothetical constant

d_0 = hypothetical difference

$\sigma^2, \sigma_1^2, \sigma_2^2$ = unknown population variances

σ_0^2 = hypothetical variance

p, p_1, p_2 = unknown population proportions

p_0 = hypothetical proportion

$\bar{x}, \bar{x}_1, \bar{x}_2$ = sample means

s^2, s_1^2, s_2^2 = sample variances

n, n_1, n_2 = samples sizes

s_p^2 = pooled variance

ν, ν_1, ν_2 = degrees of freedom

$\bar{d}$ = average of the differences for paired observations

s_d = standard deviation of the differences for paired observations

$\hat{p}, \hat{p}_1, \hat{p}_2$ = proportions calculated from a sample: $\hat{q} = 1 - \hat{p}$; $\hat{q}_1 = 1 - \hat{p}_1$; $\hat{q}_2 = 1 - \hat{p}_2$

α = level of significance (usually 0.10, 0.05, or 0.01)

t_α or $t_{\alpha/2}$ = a value of the "t" distribution with α or $\alpha/2$ probability

$x^2_\alpha, x^2_{\alpha/2}, x^2_{1-\alpha}, x^2_{1-\alpha/2}$ = a value of the χ^2 distribution with α, $\alpha/2$, $1-\alpha$ or $1-\alpha/2$ probability

$f_\alpha, f_{\alpha/2}, f_{1-\alpha}, f_{1-\alpha/2}$ = a value of the f distribution with α, $\alpha/2$, $1-\alpha$ or $1-\alpha/2$

$Z_\alpha, Z_{\alpha/2}$ = a value of the Z distribution with α or $\alpha/2$ probability

Analysis of variance is a test to compare more than two sample means. It permits the decision-maker to conclude whether or not all means of the populations under study are equal, based upon the degree of variability in the sample data. For detailed procedures see references.

Regression analysis is the study of relationships among variables. When one wishes to use a relationship (equation) between two or more variables to improve the estimation of population means for one of the variables, then the problem is one of **regression**. Depending upon the nature of the problem, it is necessary to distinguish between simple and multiple linear regression analyses and simple and multiple curvilinear regression analyses.

A correlation problem differs from a regressional problem in that one is concerned with a measure of the relationship (association) between two or more variables. The final product of a correlation analysis is the correlation coefficient, on the other hand, the final product of a regression analysis is a regression equation.

For formulae and procedures for regression and correlation analyses, consult the references.

Sampling

In a general sense, sampling is the selection of a portion (sample) of a population for measurement in order to make estimates or inferences about the entire parent population. Clearly, it is often extremely expensive (or perhaps impossible) to obtain measurements of the entire population. For a basic treatment of the sampling theory and applications, the reader is referred to (among others) Cochran (1977) and Jessen (1978).

Simple random sampling

The simplest method of selecting a (representative) sample is that of simple random sampling which is defined as follows: If a population consists of N items (sampling units) and if a sample of size n is selected from this population such that every distinct sample of size n has the same chance of being selected, the sample is defined as a simple random sample and the design, a simple random sampling design. This design is only applicable if the number of population items is small and a complete list of these items is easy to construct; it is seldom if ever cost-efficient.

Stratified random sampling

In stratified random sampling a population consisting of N items is first divided into L non-overlapping, less variable subpopulations (strata) of size N_1, N_2, …N_L, respectively. Then a simple random sample (as defined above) of size n_h, $h = 1, 2 \ldots L$, is taken from each stratum. The resulting sample is called a stratified random sample and the design, a stratified random sampling design. Stratified sampling requires some prior knowledge about the population being sampled and it is a common technique in forest sampling. When properly applied, stratified sampling can result in more precise estimates than those obtained by simple random sampling.

Cluster sampling

Cluster sampling has a superficial resemblance to stratified sampling, but it has sharply contrasting properties. The items in a population are first divided into N groups (clusters) such that each item is contained in exactly one cluster, a simple random sample of n clusters is selected, and then all items in each sampled cluster are observed. The resulting sample is called a cluster sample and the design a cluster sampling design. Cluster sampling is often simpler and more practical, but it usually can lead to substantial loss in precision compared to simple random samples of the same number of elements. The design should only be used when there are compensating advantages of cost in operation, which more than not offset the loss in precision so that greater precision per unit cost is achieved.

Multistage sampling

In multistage sampling, a population is divided into N groups (primary stage units, PSUs), each of which is made up of smaller units of size M_i, $i = 1, 2 \ldots N$ (secondary stage units, SSUs) which in turn could be made up of still smaller units (tertiary stage units, TSUs), and so on. A random sample n would be chosen from the psus, a random subsample of the SSUs would then be taken in each of the n PSUs and the procedure would be continued to the desired stage. The resulting sample is called a multistage sample and the design is a multistage sampling design. Multistage sampling provides a sample that can be cost-efficient since it clusters the sample in the higher level (larger) sample units to reduce the travel cost between measurement units.

Ratio estimation

Ratio estimation employs a relationship between an auxiliary variable which is known for each element in the population and the variable of interest to improve the precision of estimates. The relationship between the variable of interest and the auxiliary variable is determined from a sample and then used to adjust auxiliary variable parameters (i.e. mean, total) to arrive at corresponding estimates for the variable of interest. This is an efficient procedure when there is a good relationship between the auxiliary variable and the variable of interest and the auxiliary variable parameters can be simply obtained. Ratio estimators, average ratio estimators and regression estimators are all examples of ratio estimation. The best approach to use depends upon the nature of the relationship between the variable of interest and the auxiliary variable.

Multiphase sampling

Multiphase sampling is commonly confused with multistage sampling. Multiphase sampling consists of selecting a large (first phase) sample of an auxiliary variable X. A subset of the first phase units are selected and an accurate measurement made of the desired (primary) variable Y. The processes may be repeated for several phases of subsampling, and the whole process is called a multiphase sampling design. For example, in operational forest inventories, basal area may be used as an auxiliary variable X to estimate timber volume Y. The design assumes that the observations of the X are paired with the Y, that there is a strong relationship between the X and

Y and that this relationship can be estimated, and that X is much less expensive to measure that Y.

Systematic sampling

In systematic sampling, the sample units are selected at fixed intervals throughout the population. The design is often used when it is difficult to obtain a simple random sample. Statistical analysis is usually performed assuming the sampling units were selected at random.

Variable probability sampling

In variable probability sampling, each item in the sample is selected with a different but known probability (which should be made as nearly as possible proportional to the values of the variable in the population). Examples of variable probability sampling in forestry include (1) 3P sampling in which trees are selected with probability proportional to predicted values, (2) Prism (or point) sampling in which trees are selected with probability proportional to basal area, and (3) Triangle sampling in which trees are selected with probability proportional to ground area occupied by the trees. These sampling techniques are being increasingly used in combination with other designs. Details of these techniques can be found in, for example, Grosenbaugh (1965), Omule (1981), Dilworth and Bell (1968), and
Fraser (1977).

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FOREST INVENTORY

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FOREST INVENTORY[1]

Decisions, such as choosing among conflicting land uses, designing the size and location of wood processing plants, or selecting the best area for a new camping site, require current and accurate information on the present status of the forest and the possible future status of the forest. A *forest inventory* is a description of the type and quality of forest resources present in an area and the location of these resources.

Included in a forest inventory are maps of the resources to show locations (spatial information), and data files and summaries containing area measurements, tree and stand attribute data, vegetation patterns, habitat assessments, and other information (attribute information). In forest inventory design, the steps and procedures needed to obtain the desired spatial and attribute information are developed. The design begins with a statement of objectives and ends with a plan for retrieval of the desired data and details on how the data will be processed, stored, and displayed.

Continuing development in instrumentation, remote sensing technology, and data storage and manipulation has greatly changed how data can be collected, stored, and displayed over the past several decades. Nevertheless, the basic principles of inventory design remain relatively unchanged. The challenge is to collect data that will provide the information necessary for various forest management decisions today and into the future in an efficient manner. Forest inventory design involves aspects of a variety of disciplines and techniques including geographic information systems (GIS), mensuration, remote sensing, sampling design, and statistics. Many of these topics are covered elsewhere in this handbook. In this chapter, an introduction to tree and stand measurements, field sampling, and growth and yield measurements is given, along with specific forest inventory examples from BC.

Tree and Stand Measurements for Inventories

Diameter

Diameter measurements express an aspect of tree size, and may be made at any point along a tree, branch, or log. These measurements can either include the bark (termed diameter outside bark) or exclude the bark (termed diameter inside bark).

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[1] Parts of this chapter have been adapted from: Marshall, P.L. and V.M. LeMay. 1989. Forestry 237: Introduction to Forest Mensuration and Photogrammetry. 166 pp. UBC Access Guided Independent Studies, The University of British Columbia, Vancouver, BC, Canada; and LeMay, V.M. and P.L. Marshall. 1990. Forestry 238: Forest Mensuration. 213 pp. UBC Access Guided Independent Studies, The University of British Columbia, Vancouver, BC, Canada.

Outside bark diameters are by far the most common. Since diameter is strongly related to tree volume and biomass, equations to predict tree volume or biomass are often based on diameter.

The most common point to measure diameter on a tree is termed "breast height" (dbh). In BC, breast height is defined as 1.3 m above ground on the high (upper slope) side of a tree (Figure 1). The point to measure is standardized to allow comparisons among trees. Breast height is the standard location because it can be more easily reached and is high enough on most temperate tree species to be above any butt swell that may be present.

A diameter tape is commonly used in BC to measure diameters that can be easily reached. A diameter tape is either metal or cloth, contained in a closed spool made

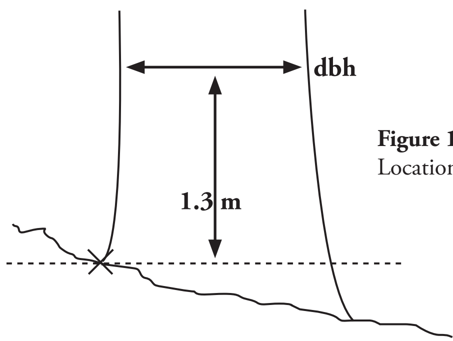

Figure 1:
Location of breast height on a tree.

of metal or hard plastic. There is a "pop-out" handle on the side of the spool for winding in the tape, and a hook at the free end of the tape to attach the tape to the bark of a tree. There are two scales on the tape. The outside of the tape is calibrated in millimeters times π, which allows the user to measure the circumference of a tree but read diameter off the scale, since circumference of a circle is π times diameter. The scale on the other side is in millimeters.

Another comonly used diameter-measuring device for easy to reach diameters is a caliper. Small calipers are used to measure root collar diameter of seedlings, and larger ones are used to measure larger diameters.

Measurements of upper stem diameters are required for more accurately estimating tree volume, to obtain measures needed for constructing volume or taper equations, and for determining the merchantable point on a stem. These diameters can be measured by felling the tree. Alternatively, a Criterion Laser or a Spiegal Relascope can be used for upper stem diameters in BC. Both of these instruments work on the principle of a fixed angle (sometimes known as a optical fork). A horizontal scale with marks (or bands) a certain width apart is used to determine the diameter of the tree. The factor for converting a measurement in the instrument units (marks or bands) to centimeters depends upon the horizontal distance the instrument is away from the tree. The further the instrument is away from the tree, the larger the diameter represented by one mark or band. Since diameter measures will be outside bark, a reduction based on measured or estimated bark thickness is needed to obtain inside bark diameters.

Height

Total tree height is the distance between the ground and the tip of the tree, commonly recorded in metres. Tree height is closely related to the quantity and quality of the wood in the bole of the tree and may be used to indicate site quality (discussed later in this chapter).

As well as total height, the height to the live crown (the distance between the ground and the lowest living branch) is sometimes measured to indicate tree vigor and growth. Also, merchantable height between the ground and some upper stem diameter is often measured.

Direct measurements of height using a measuring tape or telescoping pole can only be obtained easily for small trees. For larger trees, direct measurement requires falling the tree, and measuring along the bole with a measuring tape.

To avoid felling large trees to obtain measurements, indirect measurements of height calculated from angles and the horizontal distance can be obtained (Figure 2).

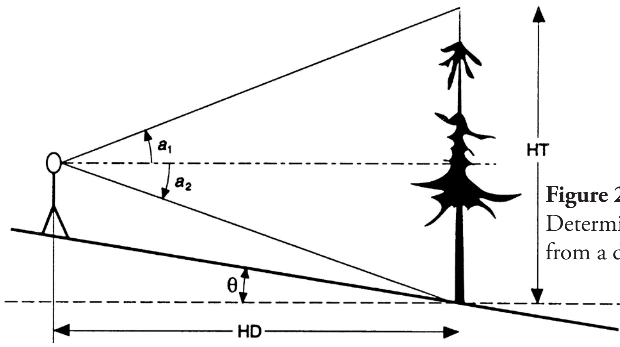

Figure 2: Determining tree height from a distance.

To obtain the measurements needed, the observer stands at a known distance from the tree, at a position where both the base (or breast height) and the top of the tree can be seen. In order to make angle measurements with reasonable precision, it is a good idea to keep the angles being measured below 45° or 100% of hortizontal distance (percent scale). On flat ground, this means being at least as far away from the tree as the tree is tall. For sloped ground, more precise measurements can be obtained by standing up-slope from the tree base. Using the angles measured in percent scale, the formula to calculate height is:

$$HT = HD \times \frac{\%UP - \%DOWN}{100}$$

where *HT* is the height of the tree in m, *HD* is the horizontal distance of the device away from the base of the tree in m, *%UP* is the angle in percent measured to the top of the tree, and *%DOWN* is the angle in percent measured to the base of the tree. Note that the angle to the tree base will be negative if the base of the tree is down slope from your eye level. If the angles are measured in degrees, the appropriate formula is:

$$HT = HD \times [\tan(up) - \tan(down)]$$

where tan(*up*) is the tangent of the "up" angle and tan(*down*) is the tangent of the "down" angle. As above, the "down" angle is considered negative if it falls below the horizontal.

Often, the base of the tree is obstructed by vegetation. In that case, the angle is measured to breast height, and 1.3 m is added to the height calculation formulae given.

Any device that measures angles can be used, along with a measuring tape for horizontal differences, to obtain tree height measurements. Commonly, the Suunto clinometer is used in BC to measure the necessary angles. Newer electronic measuring devices can be used to measure the angles and the horizontal distance, and make the trigonometric calculations. Examples of such devices are the Vertex Hypsometer and the Impulse Laser.

When trees are leaning, an adjustment to the height calculation is needed, using the angle of lean from vertical (θ) (Figure 3). The height of the top of the tree above ground (*HT'*) should be obtained from a direction perpendicular to the lean of the tree, using the formulae given before. *HT'* is then corrected using:

$$HT = \frac{HT'}{sin\ (90 - \theta)}$$

HT = 30 ÷ sin(90° – 10°)
= 30 ÷ 0.985
= 30.46 m.

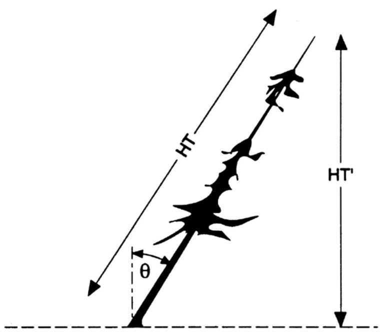

Figure 3: Determining the height of a leaning tree.

Volume

The volume of wood, as well as the size and quality, directly impact the type of wood product that can be made, and therefore, directly relates to value. Commonly, tree volume is measured inside bark. Volume can be obtained for the entire tree bole from ground to tip, for a merchantable portion of the tree, or for logs. Also, if internal decay or other deductions are taken into account, the volume becomes net rather than gross.

Measuring volume directly involves felling the tree, immersing the tree (whole or in parts) in water, and measuring the volume of water displaced using an instrument called a xylometer. Commonly, volume is indirectly measured by assuming the bole (or parts of the bole) is represented by geometric shapes. The volume formulae for four solids that are sometimes related to tree shape are:

Cylinder $V \frac{\pi \times D_b^2}{40{,}000} \times H$

Cone $V \frac{\pi \times D_b^2}{120{,}000} \times H$

Paraboloid $V \frac{\pi \times D_b^2}{80{,}000} \times H$

Neiloid $V \frac{\pi \times D_b^2}{160{,}000} \times H$

V is the volume of the solid in m^3, D_b is the diameter at the base of the solid in cm, and H is the height of the solid in m. For parts of the bole, more accurate measures of volume can be obtained using bole or log volume equations including:

Huber's Formula $$V = \frac{\pi \times D_m^2}{40{,}000} \times L$$

Newton's Formula $$V = \frac{\pi \times (D_b^2 + 4 \times D_m^2 + D_t^2)}{240{,}000} \times L$$

Smalian's Formula $$V = \frac{\pi \times (D_b^2 + D_t^2)}{80{,}000} \times L$$

where V is the inside bark volume in m^3 of the log, D_b is the inside bark diameter in cm at the bottom of the log, D_m is the inside bark diameter in cm at the midpoint of the log, D_t is the inside bark diameter in cm at the top of the log, and L is the length of the log in m. All of these formulae yield the correct volume if the log is shaped exactly like a frustum (section) of a paraboloid. Newton's formula also yields the correct volume for logs shaped exactly like sections of a cone or a neiloid. In BC, Smalian's formula is commonly used since only measurements at the top and bottom of the log are needed. This is particularly important when measurements are made on stacked logs, when diameter at the middle is very difficult to obtain.

Since trees rarely fit one geometric shape exactly, tree volume is more accurately measured by dividing the tree into logs and by using a log volume equation for each piece. Diameter and length measurements can be obtained using instruments that measure upper stem diameters, or by felling and sectioning the tree.

For many trees, tree volume is estimated using established species and location-specific relationships between volume and dbh, height and other more easily measured tree attributes. These equations are generally fitted using regression techniques based on sample measurements taken on felled and sectioned trees. Volume equations that are based on species and dbh, but not height or other measurements, are called local volume equations, since they will not be accurate for larger land areas with more variation in heights for a given dbh. Standard volume equations relate volume to dbh and height. Because height is included in the equation, these equations tend to apply to a given species over a broader area. Form class volume equations relate volume to dbh, height, and some measure of form (e.g. an upper stem diameter measurement at a specified distance up the stem). These equations are the more accurate, but require an additional, expensive, upper stem diameter measurement.

Standard volume equations were developed by the BC Ministry of Forests based on the logarithmic form of Schumacher's volume equation:

$$\log_{10}(Vol) = b_0 + b_1 \times \log_{10}(DBH) + b_1 \times \log_{10}(HT)$$

where Vol is the inside bark volume of the bole of the tree from ground to tip in m^3, b_0, b_1, and b_2 are regression coefficients, *DBH* is the diameter outside bark at breast height in cm, and *HT* is the height of the tree in m. This equation has been fitted separately to a large amount of data obtained from felled trees for different species, broad regions, and maturity classes (mature and immature). Whole stem cubic volume equations are given at the end of this chapter. To obtain merchantable volume (MV) from a given stump height (usually 30 cm in BC) to a specified minimum top diameter inside bark, the volume from these equations must be reduced. The BC Ministry of Forests has tabulated percent reduction (PR) factors for a variety of species, sizes, maturity classes, and regions.[2] These percent reductions are used in the following equation:

$$MV = Vol \times \frac{100 - PR}{100}$$

To further reduce the volume for internal decay, waste (solid wood that is not retrievable due to decay), and breakage during falling, deductions to merchantable volume have been estimated for most species and locations in BC. The percentage losses vary by size, maturity class, and risk class, estimated from sample data.[3] Up to three risk classes are identified for a given species and maturity class based on dbh and a number of external indicators of decay, such as dead and/or broken tops, frost cracks, and scars.

Standard volume functions have been replaced by taper equations for volume estimation in BC. Taper functions predict the diameter inside bark for a given height above ground, dbh, and height. These functions can be integrated to obtain volume for any part of the tree bole. For example, given a stump height and minimum upper stem diameter, merchantable volume can be obtained. BC uses a form of taper equation known as the variable exponent taper equation developed by Kozak.[4]

Pathological indicators

Trees containing internal decay often have external indicators of this condition. In BC, the following pathological indicators on or immediately adjacent to the bole are noted: conks, blind conks (swollen knots), scars, forks or pronounced crooks, frost cracks, trunk infections of mistletoe, rotten branches, and dead or broken tops. Occasionally, the position of the indicator on the tree is recorded as well. Details on these pathological indicators may be found in the BC Ministry of Forests Cruising Manual[5].

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[2] BC Ministry of Forests. 1976. Whole Stem Cubic Metre Volume Equations. Forest Inventory Division, Victoria, BC.

[3] BC Ministry of Forests. 1976. Metric Diameter Class Decay, Waste, and Breakage Factors. Forest Inventory Division, Victoria, BC.

[4] See: Kozak, A. 1988. Variable-Exponent Taper Equation. Canadian Journal of Forest Research 18:1363-1368. More information on its application in cruise compilations may be found at: www.for.gov.bc.ca/ *then navigate to Revenue Branch and Manuals.*

[5] BC Ministry of Forests. 2002. Cruising manual. Revenue Branch, Victoria, BC. An up-to-date copy of the manual can be obtained at: www.for.gov.bc.ca/ *then navigate to Revenue Branch and Manuals.*

Age

Other than keeping a record of when a tree is established, the most accurate way of determining the age of temperate tree species is to count the number of anual radial growth rings, as each ring represents one year of growth. In standing trees, an increment borer can be used to bore into the tree and extract a sample of the rings (core sample). The bit is bored into the tree a sufficient depth to at least reach the pith. The extractor is then inserted and the bit twisted one complete turn counterclockwise (to detach the core), and the extractor and the core are removed. In order to obtain an exact age, the pith must be included in the core. Often the core is taken at breast height where it is easier to obtain. Corrections to total age, based on average height growth rates for a given species and site quality class, can be estimated, and can be determined using a package called "Site Tools" on the Ministry of Forests web site (www.for.gov.bc.ca/ *then navigate to Research Branch and Growth and Yield*).

Coarse woody debris

Coarse woody debris (CWD) is defined as dead woody material, larger in diameter than some minimum size (often 7 cm). It may include standing dead material, but often is limited to downed material. CWD is an important structural component in forests, and is linked to both biodiversity and ecosystem processes.

There are a variety of CWD parameters that may be of interest, but often the primary focus is on its volume (or biomass) on a per ha basis. CWD may be sampled in a number of ways, including using fixed-area plots and line transects, covered later in this chapter.

Other variables

Other than these common measures on standing trees, measurements can be made for shrubs, herbs, and other plant layers, and on forest animals. The BC Ministry of Sustainable Resource Management has a series of manuals for measuring a variety of attributes on their Terrestrial Information Branch web site.

Field Sampling Procedures for Estimating Stand Attributes

Commonly, stands of trees are measured by locating groups of trees (plots) either randomly or systematically over the forested area. Fixed area and variable radius plots are frequently used. Variations in design are used to improve efficiency, and to alter the design when a particular attribute is of interest. A variety of sampling designs are covered elsewhere in this handbook.

An innovative sampling design for timber attributes is called "3P sampling". This was designed to measure timber attributes for small land areas. A short description of this very efficient design is also given in this section.

Fixed-area plots

Fixed-area plots cover a specified area of ground (e.g. 0.04 ha). Attributes of interest for all trees that fall within the confines of the plot boundary are usually measured or estimated. Fixed area plots are also commonly used to measure other variables, including vegetation other than trees. Each plot represents one sampling unit.

Circular, square, and rectangular plots are probably the most common shapes. Circular plots are most commonly used in BC, because their perimeter is less, leading to fewer trees on the edge (borderline trees). Also, circular plots are usually easier to lay out on the ground and it is easier to correct for horizontal distance on sloped ground than it is for other shapes.

Plot size is usually determined based on the number of trees desired, on average, in a plot. The intent is to get a good coverage of an area by establishing a reasonable number of plots throughout, while maintaining efficiency by measuring a suitable number of trees on each plot. Plots should be large enough to capture the variation in tree species and sizes, and small enough that the time needed to obtain the measurements on the plot is practical. Experience based on estimating volume per ha in BC's forests suggests that 10 to 20 trees per plot, on average, would represent a reasonable compromise. For example, to obtain an average of 20 trees in each plot for a stand that has approximately 400 stems per ha on average, the plot size should be:

$$\textit{plot size (ha/plot)} = \frac{\textit{desired stems per plot}}{\textit{estimated stems per ha}} = \frac{20}{400} = 0.05\ \textit{ha}$$

Using a circular plot, the radius for these plots would be:

$$\text{radius in m} = \sqrt{\frac{\text{plot area in ha}}{\pi} \times 10000\ \text{m}^2/\text{ha}} = \sqrt{\frac{0.05\ \text{ha}}{\pi} \times 10000\ \text{m}^2/\text{ha}} = 12.62\ \text{m}$$

The measurements made for trees in a plot depend on what information is desired. Commonly, species, dbh, and height of each tree are obtained, based on a minimum tree size (e.g. all trees with dbh > 10 cm). Each tree in the plot represents a number of trees on a ha (expansion factor). The expansion factor for fixed area plots is the inverse of the plot size. For 0.05 ha plots, each tree represents 1/0.05 = 20 stems/ha.

Example

Five trees are in a fixed area plot of 0.01 ha (Table 1). Each tree represents 100 stems/ha. Therefore, this plot represents 500 stems/ha. Volume and basal area are calculated for each tree, and then expanded to a per ha basis using the stems per ha represented by each tree.

Table 1:
Example of calculations for a single 0.01 ha fixed-area plot. The details in the shaded columns represent data collected in the field. The numbers in the clear columns represent calculations.

Tree #	Stems per ha	Species[a]	dbh (cm)	Height (m)	Basal area per tree[b] (m^2)	Basal area per ha (m^2/ha)	Volume per tree[c] (m^3)	Volume per ha[c] (m^3/ha)
1	100	Pl	20.0	20.0	0.0314	3.14	0.209	20.9
2	100	Pl	25.0	21.0	0.0491	4.91	0.344	34.4
3	100	Pl	22.1	19.0	0.0384	3.84	0.243	24.3
4	100	Sw	29.5	19.5	0.0683	6.83	0.444	44.4
5	100	Pl	23.2	21.5	0.0423	4.23	0.303	30.3
Totals	**500**					**22.95**		**154.3**

[a] Pl is the species code used in BC for lodgepole pine (*Pinus contorta*) and Sw is the species code for white spruce (*Picea glauca*).

[b] Basal area in m^2 is calculated as $\frac{\pi \times dbh^2}{40,000}$, where dbh is measured in cm.

[c] Tree volumes were calculated using the BC Ministry of Forests (1979) volume equations.

Each plot would be summarized in a similar manner, and then combined for the entire area, using the appropriate equations for the sampling design used. Often systematic sampling is used, sometimes within a stratified framework. Generally, systematic designs are analyzed using either simple random sampling, or when stratified, stratified random sampling procedures. Formulae appropriate for these techniques are provided elsewhere in this manual.

Variable-area plots

Variable-area plots are also known by a number of other names including prism plots, poly-areal plots, horizontal point samples, variable-radius plots, relascope plots, and angle-count samples. For variable-area plots, a point is located, and different sized circular plots are established. The plot size is proportional to dbh, resulting in a different number of stems per ha, but a constant basal area per ha represented by each "in" tree. Small trees must be closer to the centre of the plot to be "in" the plot, because a small plot size is used for these trees. Since a small plot size is used for small dbh trees, the number of stems per ha represented by small trees is large. Conversely, the number of stems per ha represented by each large dbh tree is small, since they would be based on a large plot size.

Variable-area plots could be established in the field by putting in many different sized fixed area plots at the located point. However, this would be quite time consuming to do. An alternative approach was developed over 50 years ago by an Austrian scientist named Walter Bitterlich. He suggested that this could be more efficiently done by projecting an angle from the plot centre (Figure 4).

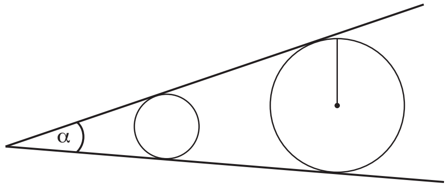

Figure 4: Projection of a critical angle (view looking down; circles represent the cross-sections of tree stems at breast height).

As can be seen from Figure 4, as the distance from the vertex of the angle increases, a tree would have to have a larger dbh in order to just touch the sides of the angle projection. Using this approach, the plot size for a tree with a given dbh is based on a radius just equal to the distance from the plot centre (angle vertex) to the point where a tree with that dbh would just touch the sides of the angle projection. This radius, called the critical distance (*cd*), varies with the dbh of the tree and the size of the critical angle α. For a small dbh tree, the plot size would be small; a tree would have to be close to the plot centre to be "in" the plot. A large dbh tree could be further away from the plot centre and still be "in" the plot (larger plot size). Therefore, a tree is considered to be "in" a plot if its dbh is greater than the width of the fixed angle. The plot area for each tree is based on a circle with the radius equal to the critical distance.

Since the stems per ha are small for large trees, the basal area per ha is constant over all "in" trees. This constant is called the basal area factor (*BAF*), which varies with the size of the projected angle. Also, the ratio of the tree dbh to the critical distance remains the same for all trees in the plot, and this is termed the angle constant (k). Because *BAF*, the projected angle, and the angle constant are all related, knowing one of these will lead you to the others using trigonometry. A larger projected angle results in a larger *BAF*.

In BC, usually the *BAF* is known for the angle projection device used. Given a *BAF* in m^2/ha, and the dbh in cm, the critical distance in metres is calculated as:

$$cd(m) = \frac{0.5 \times \text{dbh}}{\sqrt{BAF}}$$

Common devices used in BC are a wedge prism and a Spiegel relascope. The wedge prism bends light, resulting in a shifted image of a tree as viewed through the prism (Figure 5). The prism is held over plot centre, since the vertex of the fixed angle begins at the prism, and the tree is viewed at breast height. If the tree as seen above and below the prism overlaps with the tree viewed through the prism, the tree is considered to be "in" the plot. This means the tree is larger in dbh than the projected angle at that distance from the plot centre. In other words, the tree is closer to plot centre than the critical distance for a tree of this dbh. If the two images of the tree do not overlap, the tree is considered "out" of the plot. If the edges of the two images just touch, the tree is considered "borderline". The horizontal distance from the centre of the tree to the plot is compared to the critical distance calculated for the tree dbh; if this distance is shorter than critical distance, the tree is "in".

For sloped ground, corrections to the angle projected must be made in order for the angle to represent the correct critical distance. Tilting the prism at an angle equivalent to the slope results in a smaller angle, correcting for the slope. Any tree which is difficult to see at dbh, or for which the decision is not clear, should be treated as a borderline tree.

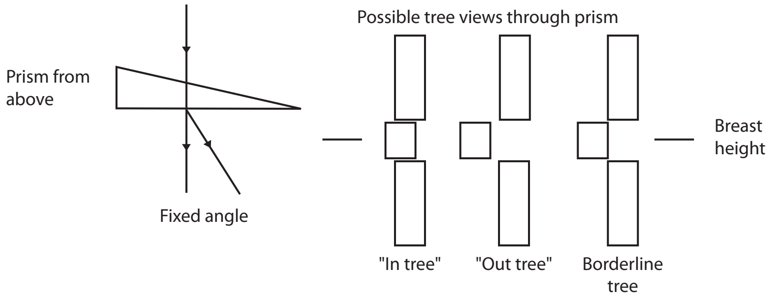

Figure 5: Functioning of a wedge prism.

With a relascope, a number of bands on the internal scale are selected and used to project the angle. The band widths are such that *BAF* equals the number of wide bands squared. Thus, if a *BAF* of 4 is desired, then two wide bands would be used. For a *BAF* of 6.25, two and one half wide bands would be used. ($2.5^2 = 6.25$). The relascope is held over plot centre. If the tree is covered by the desired number of bands, it is "out" of the plot. If it appears wider than the desired number of bands, then it is "in" the plot. If the tree is the same width as the desired number of bands, then it is "borderline", and the distance from the plot centre to the tree is compared to the critical distance as with the prism. Sloped ground is automatically accounted for using a relascope if the brake is released, since the tapering of the band widths alters the projected angle accounting for the difference between slope distance and horizontal distance.

A quick and easy to use angle projection device is your thumb (Figure 6). Your eye is the beginning of the projected angle, and your thumb defines the sides of the angle. Viewing the tree at breast height, if the tree appears wider than your thumb, the tree is "in" the plot, if the thumb appears wider, then it is "out" of the plot, and a tree as wide as the thumb is "borderline". Thumbs are not as precise as calibrated angle devices, and should only be used in reconnaissance surveys.

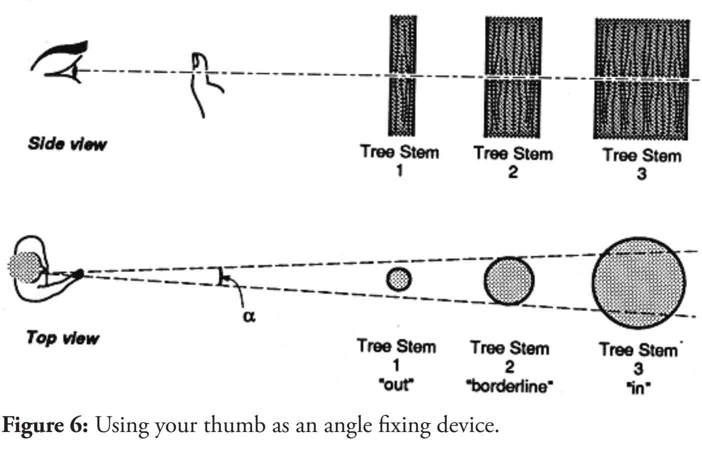

Figure 6: Using your thumb as an angle fixing device.

Although the *BAF* of most angle devices is given when you buy an instrument, this should be double-checked. This can be done by locating a target of known width at 1.3 m above a flat surface. Then, move backwards from the target while projecting your angle, until the target is just "in". The distance between you and the target is the critical distance for the target width and the angle used. The *BAF* for the device is then calculated as:

$$BAF\ (\text{m}^2/\text{ha}) = 2{,}500 \times k^2 = 2500 \times \left[\frac{\text{width of target (m)}}{\text{critical distance (m)}}\right]^2$$

The choice of which *BAF* to use is somewhat arbitrary. A larger *BAF* will result in less "in" trees, since each tree represented a greater basal area per ha. Once a *BAF* is selected, it should remain constant for sampling a given area to avoid the bias that occurs if the *BAF* is selected at the sampling point. Experience has indicated that between 6 and 10 "in" trees per plot on average works well for BC conditions. The easiest way to determine the size of *BAF* to use is to do a few trail sweeps with any *BAF*, count the "in" trees. If there are too many "in" trees, a larger *BAF* should be selected. These "test" sweeps should be done away from selected plot centers to avoid bias. For Coastal BC where trees are larger, *BAFs* of 10 m^2/ha or higher are commonly used. For Interior BC, *BAFs* of 2 to 6 m^2/ha are more common.

Example

The basal area per hectare for each tree is constant and equal to the *BAF* used (Table 2). The five "in" trees for this plot therefore represent 20 m^2/ha, since a *BAF* of 4 was used. The stems per ha for each tree vary by tree size, since the plot size varies with tree size, and is calculated by:

$$TF_t = \frac{BAF}{ba_t} = \frac{BAF \times 40{,}000}{\pi \times dbh_t^2}$$

where ba_t is the basal area of "in" tree t in m^2, dbh_t is for tree t in cm, and TF_t is the stems per ha represented by tree t (tree factor). As with fixed area plots, the volume per tree can be expanded to a volume per ha by multiplying by the stems per ha. This is then summed over all "in" trees.

As is the case for fixed-area plots, each variable-area plot would be summarized in a similar manner, and then summarized using the appropriate equations for the sampling design used for the entire area.

3-P Sampling

3-P sampling was developed by L.R. Grosenbaugh in the early 1950s to measure timber attributes of small land areas. Each tree is visited and a prediction (estimate) is made. A sample of these are then selected for precise measurements of the attribute of interest, where greater probability of selection is given to those trees with higher predictions. The use of 3-P refers to the fact that it involves Probability Proportional to Prediction, and hence the name PPP or 3-P sampling.

The attributes of interest and the attribute being predicted may be similar (e.g. measured tree volume and predicted tree volume) or different (e.g. measured tree volume and predicted tree basal area). However, it is important that there be a strong linear relationship between the two attributes to obtain narrow confidence intervals for a given sampling effort.

The details of 3-P sampling are not given here. The interested reader is directed to other sources.[6]

Table 2:
Example of calculations for a single variable-area plot with a BAF of 4.0 m^2/ha. The details in the shaded columns represent data collected in the field. The numbers in the clear columns represent calculations.

Tree #	Species[a] (cm)	dbh (m)	Height	Stems per ha	Basal area per tree[b] (m^2)	Basal area per ha (m^2/ha)	Volume per tree[c] (m^3)	Volume per ha[c] m^3/ha)
1	Pl	20.0	20.0	127.39	0.0314	4.00	0.209	26.62
2	Pl	25.0	21.0	81.47	0.0491	4.00	0.344	28.02
3	Pl	22.1	19.0	104.17	0.0384	4.00	0.243	25.31
4	Sw	29.5	19.5	58.57	0.0683	4.00	0.444	26.00
5	Pl	23.2	21.5	94.56	0.0423	4.00	0.303	28.65
Totals				**466.15**		**20.00**		**134.62**

[a] Pl is the species code used in BC for lodgepole pine (*Pinus contorta*) and Sw is the species code for white spruce (*Picea glauca*).

[b] Basal area in m^2 is calculated as $\frac{\pi \times dbh^2}{40{,}000}$ where dbh is in cm.

[c] Tree volumes were calculated using the BC Ministry of Forests (1979) volume equations included at the end of this chapter.

Sampling for CWD

Sampling for CWD is commonly based on either fixed-area plots or on line intersect sampling (LIS) in BC. For both of these, points are randomly or systematically located over the land area, and then either a fixed-area plot or a line is established at each point. Summaries are then obtained by averaging the values over the plots or the lines, and simple random sampling equations are used to calculate confidence intervals. LIS theory is available from other sources and is not presented here.[7]

Fixed-area plots for CWD measures are often circular and relatively small (e.g.

[6] A number of forest mensuration or forest measurements textbooks provide summaries of 3-P sampling. Two examples are: (1) Avery, T.E., and H.E. Burkhart. 2002. Forest measurements. Fifth Edition. McGraw Hill; (2) Husch, B., T.W. Beers, and J.A. Kershaw Jr. 2003. Forest mensuration. Fourth Edition. John Wiley and Sons, Inc.

[7] Examples of sources that cover LIS theory include: (1) de Vries, P.G. 1986. Sampling theory for forest inventory. Springer-Verlag, New York. 399 pp. (Chapter 13 deals specifically with LIS) and (2) Marshall, P.L., G. Davis, and V.M. LeMay. 2000. Using line intersect sampling for coarse woody debris. BC Ministry of Forests, Vancouver Forest Region Technical Report TR-003. 34 pp.

0.01 ha) for distributed CWD. Long rectangular plots may be used for areas of concentrated CWD (e.g. landings). All CWD pieces that fall within the confines of the plot would be measured. This can be interpreted in two different ways: (1) only portions of pieces that fall within a plot are measured, or (2) CWD pieces are considered to fall within a plot if their mid-point lies within the confines of the plot. The later interpretation is used if both the volume per ha and the number of pieces per ha of CWD are to be estimated. If only volume per ha of CWD is of interest, the first method can be used. To estimate the CWD volume per ha, generally the length, and the large and small end diameters are measured for each piece and Smalian's formula (see volume section of this chapter) is used to determine the piece volume. The piece volumes are summed to obtain plot CWD volume and expanded to the equivalent volume per ha.

Using LIS, all CWD pieces that are crossed by a number of line transects are measured. LIS is a form of unequal probability sampling, where the probability of a CWD piece being included as part of a sample is related to its length; longer pieces have a higher probability of being crossed by a line transect than shorter pieces. To obtain the CWD volume per ha, number of pieces per ha and average piece length, this unequal probability of selection must be taken into account. The formulae for summarizing each line transect are:

CWD volume per ha (m^3/ha): $$y_i = \frac{\pi}{8 \times L} \times \sum_{j=1}^{m_i} \frac{d_{ij}^2}{\cos \lambda_{ij}}$$

CWD pieces per ha: $$y_i = \frac{10{,}000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{l_{ij} \times \cos \lambda_{ij}}$$

Average CWD piece length (m): $$y_i = \frac{\sum_{j=1}^{m_i} \frac{1}{\cos \lambda_{ij}}}{\sum_{j=1}^{m_l} \frac{1}{(l_{ij} \times \cos \lambda_{ij})}}$$

where d_{ij} is the diameter of CWD piece j on transect i, l_{ij} is the length of CWD piece j on transect i, L is the length of each transect, λ_{ij} is the acute angle of the CWD piece from the horizontal, and y_i is the appropriate per ha estimate based on information on the CWD pieces intersected by transect i.

The vegetation resources inventory (VRI) developed for BC, summarized later in this chapter, employs LIS for determining CWD. Fixed-area plots are used for waste and residue surveys, because of the possibility of concentrated CWD and the presence of stumps in harvest areas (see details at the following web site: www.for.gov.bc.ca/ *and then navigate to Revenue Branch and manuals*).

Measurement of Growth and Yield

Growth" refers to the change in some attribute (characteristic) of a tree or stand over time. "Yield" refers to the total amount of some attribute present in a tree (or more commonly a stand) at some point in time. Yield is therefore cumulative growth.

Past growth and yield of trees and stands can be measured, but future values must be estimated. The yield of trees can be measured on standing trees by measuring the age of the tree and the variable of interest (e.g. basal area, volume, height). The change in certain tree variables can be monitored over time by re-measuring the same tree at different points in time. Past radial growth can be measured from cores obtained with an increment borer. In order to obtain measurements of growth of most other attributes at a single point in time, it is necessary to fell the tree and obtain detailed stem analysis measurements (measurement of radii at several heights along the tree stem) that will allow the tree to be "reconstructed" as it would have been at various points in the past.

The yield of a stand can be measured using a representative sample of temporary sample plots (TSPs). However, growth is measured using permanent sample plots (PSPs), often selectively located in particular species compositions, ages, densities, and sites. The locations of PSPs, and often the trees within a PSP, are marked so that the plots can be relocated on future measurement occasions. PSPs may be composed of two or more nested plots, where smaller plots are used for smaller trees. PSPs may be established with only permanent boundaries, or with permanent boundaries and tagged (numbered) trees. Additionally, some PSPs are "stem-mapped" where a record of the spatial position of each tree is obtained. PSPs are useful as monitors of growth, mortality, competition, species changes, and ingrowth. Stem-mapped PSPs also allow for quantifying the competition among trees based on the positions and sizes of neighbouring trees.

BC has several thousand PSPs of different types and ages. The BC Ministry of Sustainable Resources Management maintains databases with location and other details of many of these plots, as well as the data collected.

Generally, estimates of future growth and yield are made by applying measurements of growth and yield of trees and stands, together with tree and stand attributes and the management regime, into existing growth and yield models. (See the chapter on Stand and Forest Dynamics for details on estimating future growth and yield and see the Ministry of Forests, Research Branch web site for information on growth and yield models used in BC (www.for.gov.bc.ca/ *and navigate to Research Branch and Growth and Yield Models*). Most growth and yield models require information on site productivity and stand density as inputs, and future growth and yield estimates are the outputs.

Site quality

Site quality is an assessment of the productive capacity of a site for growing a particular species of tree. Knowledge of site quality is important since it influences the timing and type of silvicultural treatments that may be applied to an area. It is also one of the major factors that control the growth rates of trees. Measures of site quality can be divided into direct *versus* indirect measures.

Direct measures of site quality include:

1. *Historical yield records.* The yield of a stand prior to a disturbance (e.g. logging, fire) is used to assess the site after the disturbance. This approach assumes that the site conditions that influence tree growth are identical before and after disturbance. It also assumes that the species composition of the future stand will be similar to the past stand.

2. *Stand volume data.* The yield of an existing stand can be measured. However, comparisons among stands and over different ages would be difficult since stand volume varies with age and density.
3. *Stand height.* This is by far the most common approach to assessing site quality within North America. Tree height is easily measured, and the height growth of large, healthy trees of most species is little affected by quite wide ranges of density.

Indirect methods of assessing site quality use measures of other variables to indicate forest productivity. These methods are particularly useful when: 1) the species of interest is not present on the site; 2) the trees present are not representative of the growth that would occur on a young stand (e.g. old growth); or 3) environmental conditions have changed.

Indirect methods include:

1. *Overstory species relationships.* The growth of a tree species present on a site is used to infer the growth of the species of interest, based on stands where the two species grow together. This approach can work well locally; however, the growth relationship between two species can be quite variable over a range of site conditions.
2. *Lesser vegetation characteristics.* The presence and abundance of certain herbs and shrubs (indicator species) may be used to assess the quality of a site for growing certain tree species. As was the case for overstory relationships, it may be difficult to establish good relationships between indicator species and the growth of a tree species that holds over a wide geographical area.
3. *Topographic, climatic, and edaphic factors.* Relationships may be derived between tree growth and these factors, either singly or in combination. Good relationships can be established for local areas, but often weaken over larger areas.

All of these approaches are being used to some degree in BC. The use of height of some portion of the trees in a stand at a reference age, termed site index, is very common in North America. Also, the biogeoclimatic ecosystem classification (BEC) system of BC is used widely in estimating potential site productivity, in choosing which tree species to plant, and many other management decisions. More detail on site index and other related indices are given here.

Site Index

Site index is defined as the average height of a specified portion of the trees in a stand at some reference age. Site index has been found to correlate well with volume production and is used in many growth models. In order to accurately reflect site potential, trees that are measured for height and age should be among the tallest trees in the stand and free of any evidence of past leader damage. Such trees are called site trees.

In BC, the reference age for site index is 50 years measured at breast height (1.3 m above ground; breast height age) on site trees. Most site index curves developed or selected for use in BC are based on the average height and breast height age of the 100 largest (by dbh) trees per ha for the dominant species. In practice, the top height is found as the largest tree of the dominant species on a 0.01 ha plot. Only healthy, undamaged trees should be selected as site trees. Site index curves and tables are available for most BC tree species and locations from the Ministry of Forests, Research Branch web site: www.for.gov.bc.ca/ *and naviagte to Research Branch and Growth and Yield.* Also, a user-friendly tool called "Site Tools" can be downloaded from: www.for.gobc.ca/hre/sitetool/.

Estimating site index using measurements of height and age is a convenient and accurate approach to estimating site quality. However, there are conditions where other approaches are needed including:

1. *The species of interest is not present in sufficient numbers.* It is obvious that the height and age of a tree species cannot be measured if that species is not present in a stand. In addition, it is inappropriate to select site trees if the species is present, but not numerous, since it is unlikely that a sample can be obtained that truly reflects the quality of the site.
2. *The stand is very old or very young.* The best estimates of site index using site index equations are obtained from stands that are close to index age. In very young stands, it is difficult to determine which trees will be site trees in later years. Also, non-site factors immediately following regeneration (e.g. planting stock condition, competition from herbaceous species) affect a large proportion of the total height of young trees. Estimates of site index based on growth intercept techniques rather than height and age work best for young stands. The difficulty in older stands is to find site trees that have not been damaged in some fashion. The upper limit in age at which site trees can be reliably found differs with the species and stand conditions, as well as with the data used in constructing the site index equations. Current site index equations used in BC are reliable from 20 years up to at least 120 years of age.
3. *The stand is uneven-aged.* The difficulty in uneven-aged stands is to find site trees that have not been subjected to competition for light, since regeneration and saplings grow in the shade of existing trees. The trees that best reflect the potential of the site are often not the largest trees in these stands. If height and age are to be used to estimate site index in uneven-aged stands, care should be taken to select trees with no evidence of past suppression. This usually means examining radial increment on a series of cores before selecting site trees.

Growth Intercept

The growth intercept (GI) method was developed to increase the precision of estimates of site index for young stands. With this approach, site index is estimated from measurements of yearly height growth over some period of time after a tree has reached breast height. The GI technique is considered appropriate for use in BC if: (1) a growth intercept table is available for the site index species; (2) the dominant and codominant trees have at least three year's growth and no more than 30 years growth above breast height; (3) more than 500 stems per ha (of all species) are evenly distributed over the stratum; and (4) sample tree height growth above breast height appears to reflect site productivity. The latter condition may not hold if there has been severe brush competition, fertilization, widespread damage, or other factors that impact on height growth.

The first step to applying the GI technique is to determine which tree species is the site index species. Normally, this would be the leading species in a stand or some other stratum. Once this has been decided, sample trees are selected using 5.64 m radius, circular plots. A number of these plots are established across the stratum of interest. On each plot, the tree of the site index species with the largest dbh is selected as a potential sample tree. This tree is measured if: (1) it has at least three years height growth above dbh; (2) it appears to be undamaged; (3) it is in the dominant or codominant crown class and not overtopped by other trees or brush; and (4) its growth rings indicate vigourous and uniform growth. If a potential sample tree is not measured, GI information is not collected on that plot.

The trees species, total height from ground (high side) to the top of the leader, and age at breast height are recorded for sampled trees. Age at breast height is obtained from counting rings on trees felled at breast height (small dbh trees) or from increment cores taken at breast height (on larger dbh trees). Once information on species, age, and height of the sample tree is known, the site index can be determined using an appropriate table or using Site Tools. The site index assigned to a stratum is the average of the site indices determined for each of the trees in the stratum.

Growth intercept publications can be found on the Ministry of Forests, Research Branch web site: www.for.gov.bc.ca/hre/pubs/ and estimates can be obtained using the "Site Tools" package (www.for.gov.bc.ca/hre/sitetool/).

SIBEC

The SIBEC (**S**ite **I**ndex via **B**iogeoclimatic **E**cosystem **C**lassification) program has established relationships between site index and BEC subzone and site series for a variety of tree species across BC. Despite the attention given to this program over the past decade, its application can prove problematic in some circumstances. Difficulties with applying this approach include:

1. the correlation between site index and the site units vary from weak to moderately strong across species and sites;
2. it requires correct site identification;
3. not all species and sites are included in the tables; and
4. the database is small for other certain other species and sites combinations, leading to imprecise estimates.

Estimating site index via relationships with the BEC system generally does not produce as reliable estimates as using site index equations or growth intercept approaches, if stand conditions are such that either of the other approaches are appropriate. Nevertheless, there are circumstances where the SIBEC approach may provide the most reliable estimates of site quality, including when stands are less than three years breast height age, stands are very old, or the species of interest is absent from the site.

Growth intercept publications can be found on the Ministry of Forests, Research Branch web site: www.for.gov.bc.ca/hre/pubs/ and estimates can be obtained using the "Site Tools" package (www.for.gov.bc.ca/hre/sitetool/.

Measurement of density

Density of a stand is a quantitative measure of the degree of crowding present. Stocking is a qualitative assessment of the degree of crowding compared to some standard. These two terms are often incorrectly used interchangeably.

The number of stems per ha or basal area per ha are sometimes used as simple indicators of density. However, these terms carry meaning only if age or some measure of average tree size is known. Average crown closure for a stand is another simple, commonly used indicator of density that can be measured on aerial photographs. Crown closure is usually stated as a percentage, with complete crown closure given a value of 100 percent.

Density can also be expressed in the form of a factor or index. These indices normally combine some measure of quantity (e.g. numbers of trees per unit area, basal area per unit area) with some measure of average tree size. Curtis' relative density index (RD) is a combination of basal area per unit area (BA in m^2/ha) and quadratic mean diameter (diameter of a tree of average basal area in cm):

$$RD = \frac{BA}{\sqrt{\bar{d}_q}}$$

Prognosis^{BC}, a growth and yield model for mixed species stands, employs another commonly used index, the crown competition factor (CCF). This factor uses a relationship established between crown width (CW in m^2) and dbh (D in cm) of open-grown trees of the form:

$$\hat{CW} = b_0 + b_1 \times D$$

where b_0 and b_1 are regression coefficients. CCF is based on the horizontal projection of crown areas of stand-grown trees of a given dbh relative to the maximum crown area that would be associated with open-grown trees of the same dbh. To calculate it, the maximum crown area (MCA), the crown area of an open-grown tree of dbh expressed as a percentage of a ha, is calculated for every tree in some area:

$$MCA = \frac{100 \times \hat{CW}}{10{,}000}$$

The sum of these values over a hectare is the CCF. The larger the CCF, the greater the number and/or size of the trees in an area, and, therefore, the higher the density.

BC Examples of Field Sampling Procedures for Estimating Certain Stand Attributes

This final section will present a summary of the cruising and forest resources inventory procedures used in BC. The term "cruise" is applied to relatively small scale, field-intensive samples, focused on the timber component of mature stands prior to harvesting. The term "forest resources inventory" is applied to large scale, field-extensive samples, focused on quantifying a number of forest resources for planning and management purposes.

Timber cruising in BC

The following material is summarized from the *Cruising Manual*.[8] An up-to-date copy of the manual can be obtained at the following web site: www.for.gov.bc.ca/ *and naviagte to Revenue Branch and Manuals*.

Objectives

The primary objective of a cruise is to estimate the volume of timber present on the area cruised, within a specified degree of accuracy. The cruise plan and accuracy requirements are affected by the form of timber appraisal to be used, and are specified in the *Cruising Manual*. In special cases, cruising standards may be set by the Regional Manager.

For scale-based sales, the cruise provides the basis for determining the stumpage rate. The sampling objective is to obtain a sampling error less than 15% (with 95% probability) based on the total stand volume before reduction. Where the sampling error is not expected to be achieved, the minimum number of plots is specified as at least two measured plots per ha, for areas 10 ha or less in size. For areas larger than 10 ha, the minimum number of plots is equal to the number of hectares plus 10. The number of count plots[9] allowed depends on the silviculture system that will be employed (clearcutting vs. partial cutting) and the number of measured plots.

For cruise-based sales, both the estimate of the stumpage rate and billing are based on the cruise. The sampling objective is to obtain a sampling error less than 8% (with 95% probability) based on the total stand volume before reduction. Count plots may be used provided that a sampling error less than 12% (with 95% probability) is obtained using the measured plots alone.

Sampling approaches and tree measurements

Most cruises in BC involve the use of variable-area plots, although fixed-area or, more rarely, 3-P sampling may be used.

Plots are located using systematic sampling, with the sampling grid oriented in the cardinal directions. The maximum spacing allowed between plots is 200 m. The grid should be connected to valid tie-points, and the tie-point for each strip-

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[8] BC Ministry of Forests. 2000. Cruising Manual. Revenue Branch, Victoria, BC.

[9] Count plots are variable-area plots on which only a count of "in" trees is performed. These data may be combined with data collected on measured plots, via the double sampling technique, to produce more accurate assessments than would be possible using the measured plots alone.

line must be such that it is locatable at future dates. Plot centers must be clearly marked, with a reference point established on the nearest live tree to the plot center. The bearing and horizontal distance from the reference point to the center point must be written on both the reference tree and the tally card. Each cruise must be accompanied by a detailed map, showing, among other features, timber type lines and descriptions, plot locations, existing and proposed roads, locations of baselines, physiographic features, legal survey features, and status clearance and cutting boundaries.

All measured trees in a plot must be marked with a paint line or tag at the point of dbh measurement, with the numbers facing the centre of the plot. Borderline trees that are "out" should be marked with an "X". In a count plot, only the first tree is numbered and marked with an arrow indicating the direction of the tree tally. All living and dead, standing and down trees, of the commercial species identified in the *Cruising Manual* that meet or exceed the utilization limit should be included in the sample and have species recorded. Dbh should be measured on all "in" trees, and heights either measured or estimated for these trees. Pathological indicators should be recorded when observed on the bole or a merchantable secondary leader. All living and dead trees should be assigned to one of nine tree classes, reflecting their potential use, and damage codes used when damage is identifiable. The breast height ages of a sample of trees in each plot should also be measured.

The Vegetation Resources Inventory (VRI) procedure in BC

The Forest Resources Inventory (FRI) program in use in BC is managed by the Terrestrial Information Branch of the Ministry of Sustainable Resources Management. The FRI is a geo-referenced repository of current forest resources data intended to support integrated resources management decisions that need to be made in BC. The Vegetation Resources Inventory (VRI) is a component of the FRI.

The VRI is designed to answer two questions: (1) where is the resource located; and (2) how much of the resource is present within an inventory unit. The VRI is conducted via two phases. Phase I involves estimating vegetation polygon attributes from existing information or aerial photography. No ground sampling is involved in Phase I. Phase II comprises the ground sampling component of the VRI. The Phase II measurements are used to estimate the population total. The relationship between the ground estimates and the polygon estimates is used to adjust the Phase I polygon estimates, and the population total is then distributed into each of the polygons.

The BC land cover classification scheme[10]

This scheme is designed to meet provincial needs related to integrated resources management decisions, as well as national and international needs focused more on global vegetation accounting. Classification is done using a hierarchy based on

[10] The reference for the material in this section is: Ministry of Sustainable Resources Management. 2002. Vegetation Resources Inventory: The BC Land Cover Classification System, Version 1.3. Terrestrial Information Branch.

current cover. The first level is whether or not the land is vegetated, non-vegetated, or unreported. There are four subsequent levels for each of the vegetated and non-vegetated types, with the nature of these levels dependent upon the initial type.

The second level within the vegetated type is land cover type (treed or non-treed). The third level is landscape position (wetland or upland for the treed land cover type and wetland, upland, or alpine for the non-treed land cover type). The fourth level is vegetated types. For each of the landscape positions within the tree land cover type, the vegetated types recognized are coniferous, broadleaf, or mixed. For each of the landscape positions within the non-tree land cover type, the vegetation types recognized are shrub tall, shrub low, herb, and bryoid. The fifth level is density classes. Each of the vegetation types, with the exception of the alpine bryoid, is divided into dense, open, and sparse. The alpine bryoid type is simply divided into closed and open density classes.

The second level within the non-vegetated cover type is land cover type (land or water). The third level is landscape position (wetland, upland, or alpine). The fourth level, only applicable to each of the landscape positions within the "land" land cover type, is non-vegetated cover types (snow/ice, rock/rubble, or exposed land). The fifth level is entitled "non-vegetated categories" and consists of more detailed breakdowns of each of the landscape positions / non-vegetated cover type classes.

Classification is applied at the delineated polygon level, based on polygon attributes estimated using photo interpretation (Phase I of the VRI). The classification of each polygon is summarized as a seven letter code. The coding for the classes within each of the levels of the classification scheme are provided in the manual cited in footnote 11.

Ground sampling procedures[11]

Ground sampling procedures for the VRI are intended to cover the entire landbase of BC, irrespective of ownership or vegetation values. Sampling units (plots) are selected within an inventory unit, often following pre-stratification, using a sampling design based on probability proportional to size with replacement (PPSWR). The sampling units are not moved, but rather assessed where they fall. Measurements of tree and other attributes on a plot are completed and recorded in the field and made to known levels of precision.

Once the population data (polygons and their associated attributes) have been assembled for an inventory unit, the unit should be stratified. Stratification of polygons is initially done using the land classification categories: non-vegetated, vegetated non-treed, and vegetated treed. Treed polygons are then further stratified by leading species, or species group, and three or four volume classes or surrogates (e.g. basal area classes). The number of sample points to be located in each stratum is usually partially specified in the VRI Strategic Inventory Plan, but generally is at least 15. The selection of sampling unit locations within a stratum proceeds in two stages. In the first stage, polygons are selected from the population using PPSWR.

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[11] BC Ministry of Sustainable Resources Management. 2002. Vegetation Resources Inventory: Ground Sampling Procedures. Version 4.3. Terrestrial Information Branch.
BC Ministry of Forests. 2001. Vegetation Resources Inventory: Sample Selection Procedures for Ground Sampling. Version 3.1. Resources Inventory Branch.

This sampling design ensures that larger polygons have a larger probability of being selected for sampling than smaller polygons and that polygons may be selected more than once. In the second stage, a sampling point is selected randomly, usually without replacement, from points on a pre-established 100 m provincial grid that fall within the selected polygon. Polygons will have as many sampling points as the number of times they have been selected. Detailed instructions have been established for locating and documenting plot centre locations.

The basic sampling plot design is a five-point cluster, with an integrated plot located at the centre of the cluster and four auxiliary plots located 50 m from the plot centre in the cardinal directions. The integrated plot centre is the location around which detailed information is collected; all information is attached to the plot centre point. Detailed descriptions of the sampling methods and data to be collected are provided in the *Ground Sampling Procedures Manual*. The auxiliary sample plots are used to supplement the basal area information collected on the integrated plot; only tree measurements are taken on the auxiliary plots.

Ministry of Forests Volume Equations

The following equations are taken from *Whole Stem Cubic Metre Volume Equations* published by the Ministry of Forests in 1976.

The volume equations provide gross volume in m^3 for entire tree stems, inside bark, including stump and top. In the following equations, D represents dbh in cm, H is total tree height in m, V is total tree volume in m^3, and *log* is the logarithm to base 10. SE represents the standard error of estimated volume for a single tree as a percent of the average, n is the number of sample trees upon which the equation is based, and FIZ is the forest inventory zones to which the equation is intended to apply. Species are arranged alphabetically according to their common name.

Broadleaf Maple (All ages)
$\log(V) = -4.536696 + 1.907850 \times \log(D) + 1.120160 \times \log(H)$
SE = ± 8.3%
n = 264
FIZ: A, B, C

Cottonwood (All ages)
$\log(V) = -4.648431 + 1.735180 \times \log(D) + 1.356010 \times \log(H)$
SE = ± 10.6%
n = 347
FIZ: A to J, inclusive

Cottonwood (All ages)
$\log(V) = -4.586123 + 1.778590 \times \log(D) + 1.250760 \times \log(H)$
SE = ±7.3%
n = 573
FIZ: K, L

Douglas-fir (Immature – up to 120 years)
$\log(V) = -4.319071 + 1.813820 \times \log(D) + 1.042420 \times \log(H)$
SE = ± 10.3%
n = 393
FIZ: A, B, C

Douglas-fir (Mature – over 120 years)
$\log(V) = -4.348375 + 1.692440 \times \log(D) + 1.181970 \times \log(H)$
SE = ± 12.3%
n = 603
FIZ: A, B, C

Douglas-fir (All ages)
$\log(V) = -4.383102 + 1.742940 \times \log(D) + 1.156410 \times \log(H)$
SE = ± 11.2%
n = 3,032
FIZ: D to I, inclusive

Larch (western and mountain – all ages)
$\log(V) = -4.350486 + 1.723600 \times \log(D) + 1.135270 \times \log(H)$
SE = ± 12.8%
n = 756
FIZ: D to I, inclusive

Larch (tamarack – all ages)
$\log(V) = -4.370540 + 1.724890 \times \log(D) + 1.192450 \times \log(H)$
SE = ±6.3%
n = 203
FIZ: K, L

Lodgepole pine (All ages)
$\log(V) = -4.349504 + 1.822760 \times \log(D) + 1.108120 \times \log(H)$
SE = ± 9.3%
n = 2,846
FIZ: A to J, inclusive

Lodgepole pine (All ages)
$\log(V) = -4.279068 + 1.898400 \times \log(D) + 0.996793 \times \log(H)$
SE = ± 7.0%
n = 1,369
FIZ: K, L

Ponderosa pine (All ages)
$\log(V) = -4.482485 + 1.954430 \times \log(D) + 1.016770 \times \log(H)$
SE = ± 16.4%
n = 672
FIZ: C to G, inclusive

Red alder (All ages)
$\log(V) = -4.431705 + 1.778590 \times \log(D) + 1.090770 \times \log(H)$
SE = ± 7.7%
n = 546
FIZ: A, B, C, J, K

Sitka spruce (Immature – up to 120 years)
$\log(V) = -4.310416 + 1.822840 \times \log(D) + 1.0057290 \times \log(H)$
SE = ± 9.6%
n = 318
FIZ: A, B, C

Sitka spruce (Mature – over 120 years)
$\log(V) = -4.368545 + 1.646990 \times \log(D) + 1.282450 \times \log(H)$
SE = ± 11.6%
n = 353
FIZ: A, B, C

Spruce species (All ages)
$\log(V) = -4.294193 + 1.858590 \times \log(D) + 1.007790 \times \log(H)$
SE = ± 9.3%
n = 4,452
FIZ: D to J, inclusive

Spruce species (All ages)
$\log(V) = -4.379777 + 1.783940 \times \log(D) + 1.146280 \times \log(H)$
SE = ± 8.0%
n = 3,018
FIZ: K, L

Trembling aspen (All ages)
$\log(V) = -4.419728 + 1.894760 \times \log(D) + 1.053730 \times \log(H)$
SE = ± 8.0%
n = 802
FIZ: A, to J, inclusive

Trembling aspen (All ages)
$\log(V) = -4.538904 + 1.834410 \times \log(D) + 1.208970 \times \log(H)$
SE = ± 8.2%
n = 1,077
FIZ: K, L

True fir species (" balsam" – all ages)
$\log(V) = -4.266202 + 1.782960 \times \log(D) + 1.103820 \times \log(H)$
SE = ± 9.6%
n = 816
FIZ: A, B, C

True fir species (" balsam" – all ages)
$\log(V) = -4.291919 + 1.872930 \times \log(D) + 0.998274 \times \log(H)$
SE = ± 10.0%
n = 3,822
FIZ: D to J, inclusive

True fir species (" balsam" – all ages)
$\log(V) = -4.350792 + 1.698090 \times \log(D) + 1.231200 \times \log(H)$
SE = ± 7.3%
n = 577
FIZ: K, L

Western hemlock (Immature – up to 120 years)
$\log(V) = -4.418820 + 1.867780 \times \log(D) + 1.099890 \times \log(H)$
SE = ± 10.9%
n = 736
FIZ: A, B, C

Western hemlock (Mature – over 120 years)
$\log(V) = -4.337451 + 1.783500 \times \log(D) + 1.120230 \times \log(H)$
SE = ± 12.7%
n = 1,276
FIZ: A, B, C

Western hemlock (All ages)
$\log(V) = -4.394633 + 1.942900 \times \log(D) + 0.998274 \times \log(H)$
SE = ± 11.2%
n = 1,785
FIZ: D to K, inclusive

Western redcedar (Immature – up to 120 years)
$\log(V) = -4.139118 + 1.716770 \times \log(D) + 1.047420 \times \log(H)$
SE = ± 11.3%
n = 438
FIZ: A, B, C

Western redcedar (Mature – up to 120 years)
$\log(V) = -4.103107 + 1.743240 \times \log(D) + 0.981729 \times \log(H)$
SE = ± 11.7%
n = 652
FIZ: A, B, C

Western redcedar (All ages)
$\log(V) = -4.178431 + 1.759950 \times \log(D) + 1.019080 \times \log(H)$
SE = ± 10.7%
n = 1,576
FIZ: D to J, inclusive

Western white pine (All ages)
$\log(V) = -4.300522 + 1.857800 \times \log(D) + 1.022250 \times \log(H)$
SE = ± 8.1%
n = 344
FIZ: A to H, inclusive

White bark pine (All ages) – same equation as western white pine
$\log(V) = -4.300522 + 1.857800 \times \log(D) + 1.022250 \times \log(H)$
SE = ± 8.1%
n = 344
FIZ: A to J, inclusive

White birch (All ages)
$\log(V) = -4.443142 + 1.909560 \times \log(D) + 1.052050 \times \log(H)$
SE = ±10.8%
n = 407
FIZ: A to J, inclusive

White birch (All ages)
$\log(V) = -4.700665 + 1.912030 \times \log(D) + 1.246160 \times \log(H)$
SE = ±8.2%
$n = 286$
FIZ: K, L

Yellow cedar (All ages)
$\log(V) = -4.187127 + 1.777360 \times \log(D) + 1.032990 \times \log(H)$
SE = ± 9.5%
$n = 302$
FIZ: A to E, inclusive, G.J.

MODELLING STAND AND FOREST DYNAMICS

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MODELLING STAND AND FOREST DYNAMICS

Thirty to forty years ago, the value of forested land over much of North America was measured largely by the amount of timber that it held, or that it could produce. Over time, increased public concerns for other forest values, such as recreation, aesthetics, and large game, led to these others uses being generally encompassed within a timber management context. More recently, forests have been increasingly recognized as being valuable for more than commodity production. The roles that forests play in regulating water and nutrient flows, fixing atmospheric carbon, and various other biological functions are seen as being fundamental to the long-term stability of the forest system. Today, timber management is seen as only one component in the sustainable management of the entire forest.

In this chapter, the basics of stand and forest dynamics are presented, together with the approaches used in British Columbia (BC) to model timber supply. Reliable predictions of future conditions, given a sequence of management activities, are integral to sustainable forest management.

Stand Dynamics (Growth and Yield)

Stand dynamics refer to the changes in stand structure (size distribution, species composition, etc.) with time. If the focus is on trees, then the relevant components of stand dynamics are often referred to as "growth and yield". Understanding the various components of growth and yield is necessary to developing, and effectively using, models that predict future stand structures under a variety of different silvicultural treatments.

Tree and stand development

Growth refers to the change in some attribute (characteristic) of a tree or stand over time. **Yield** refers to the total amount of some attribute present in a tree (or more commonly a stand) at some point in time. Clearly growth and yield are mathematically related.

If yield of some stand characteristic is plotted versus age, then growth is the slope (first derivative) of the yield curve. (See Figure 1 for an even-aged example). This growth represents the current annual increment (CAI), or the yearly growth

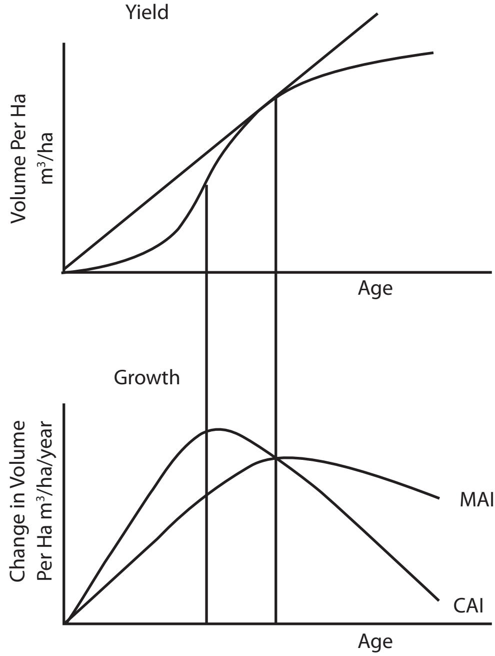

Figure 1: Example of volume growth and yield from an even-aged stand.

rate. In an even-aged stand, growth can also be represented as an average (i.e. the yield divided by the age of the stand). This type of growth is called mean annual increment (MAI). CAI is maximized at the age on the yield curve at which the slope is maximum. In even-aged stands, where volume yield has a characteristic sigmoidal shape, this age occurs at the inflection point on the curve, where a shift occurs from a convex shape to a concave shape. MAI is maximized at the age at which a straight line drawn through the origin is tangent to the yield curve. The CAI curve crosses the MAI curve at this age.

In order for growth and yield models to successfully predict future stand conditions, they should incorporate factors known to affect tree and stand growth and development. These factors include:

1. *Site quality.* Site quality refers to the totality of the physical and environmental factors that affect tree growth. Various measures and indices of site quality exist; however, site index, the expected height of some dominant component of a stand at some reference age, is the most commonly used in growth and yield models.
2. *Density.* Although it is commonly recognized that the maximum volume or basal area that can be produced on a given site is unaffected by density over a fairly wide range, density does influence the path which a stand follows towards this maximum. As is the case for site quality, various measures and indices of density exist; however, unlike site quality, there is no one measure

or index that is widely used to the exclusion of others in growth and yield models. Some of the more common measures or indices that may be used include basal area, crown competition factor (CCF), and Curtis' relative density.

3. *Species composition*. Different tree species develop at different rates on any given site. What may be poor site conditions for one species may be good site conditions for another. Also, a variety of growth patterns, often related to shade tolerance, are displayed by different species. Even within a single species, different growth rates and development patterns occur because of genetic and micro-site differences. In order to deal with species differences, growth and yield models commonly are calibrated separately for individual species, or occasionally, for groups of species.
4. *Age and/or stand structure.* In even-aged stands, the rate of growth that can occur is partly related to age, as a surrogate for stage of development. Many models developed for even-aged stands use age as one of the predictors of yield. In uneven-aged stands, there is no single age that can be used to represent the age of the stand. Models developed for predicting growth and yield of such stands frequently use some indicator of stand structure (e.g. dbh distribution) as a predictor of growth or yield.
5. *Agents of tree damage and mortality.* Certain insects, pathogens, and small mammals can damage or kill individual trees. Episodic weather events (e.g. severe wind storms, heavy wet snow) can have a similar effect. Normally, factors such as these are not incorporated directly into growth and yield models, but rather are considered to be part of the "background noise" that accounts for some of the difference between model predictions and the yield of individual stands.
6. *Management activities.* Human interventions in the dynamics of individual stands obviously have an impact on the dynamics. Such interventions can range from various forms of harvesting to genetic improvement. The impact that these activities might have can be understood through their impact on the other factors mentioned above. For example, various forms of thinning influence the stand density; fertilization impacts on site quality; genetic improvements impact on the species component.

Modelling stand dynamics

A variety of different types of growth and yield models exist, ranging from the simplicity of hand-drawn yield curves to extremely complex computer models. The first computer-based growth and yield model was introduced in the mid-1960s. Since that time, computer-based growth and yield models have become the norm. Literally thousands of such models have been developed for use under various conditions around the world. Despite the overwhelming number of these models, it is possible to group them into a limited number of categories based on how the models are structured. These categories are extremely useful because they can indicate quite a bit about the models that belong to that category.

Whole stand models

In whole stand models, stand yield (and less frequently growth) are represented by only a few equations. These models can be built using data from temporary sample plots (TSPs), permanent sample plots (PSPs), or a combination of TSPs and PSPs.[2] Whole stand models are generally initiated by average stand information (e.g. age, species composition, site quality, stems per ha, average dbh). This approach was used almost exclusively before the advent of computers because of its relative simplicity.

The advantages of whole stand models are that they use stand-level information, which is relatively easily obtained as input, and the modelling approach tends to be simple. The disadvantage is that individual tree information is lacking. However, this is only a disadvantage if individual tree information is required by the user; if only stand-level detail is of interest, then whole stand approaches can work quite well.

Yield tables or curves (or the underlying yield equations upon which these tables or curves rely) are often based on a whole stand modelling framework. Yield tables display stand conditions in tabular format, often by age, for a variety of different conditions (e.g. species composition, site qualities). Yield curves are a graphical representation of the same data. Several different kinds of yield tables or curves exist, generally classified in terms of how stand density is incorporated. Normal yield tables are based on data collected from "fully stocked" stands. This type of yield table was quite common in North America in the first half of the twentieth century, but is not widely used today, since full stocking seems to be an exception rather than a rule even in most intensively managed temperate stands. Empirical yield tables are based on data from stands with average stocking conditions. This sort of approach is often used in projecting inventory information, which may lack the single-tree data necessary for single-tree modelling approaches. Variable density yield tables explicitly incorporate some measure of stand density into the prediction of yield. This type of approach generally provides more accurate predictions of future stand conditions than either a normal or empirical approach. An example of a BC growth and yield model based on this approach is VDYP.

VDYP:[3] The Variable Density Yield Prediction (VDYP) model and its accompanying software were developed to produce empirical yield tables, specific for particular species compositions, density values, site indices, and locations in BC. The model can also be used to assign volumes to particular forest polygons following photo-interpretation and for updating the volume of forested polygons prior to a timber supply analysis or other forest-level application. Also, VDYP can be used to predict stand height dbh volume and mean annual increment at different utilization levels and ages. The data used to calibrate VDYP were a mixture of temporary sample plots (TSPs) and permanent sample plots (PSPs) from across BC.

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[2] Measurement of growth and yield data is presented in the Forest Inventory chapter of this handbook.

[3] More information on VDYP and a copy of the software can be obtained at: www.for.gov.bc.ca/hre/gymodels/VDYP/index.htm

Single-tree distance-independent models

To build these sorts of models, tagged tree data from PSPs are required; however, the tree locations do not have to be mapped. Trees are grown individually or in cohorts according to some mathematical function(s). Techniques for assigning growth and mortality among cohorts and predicting ingrowth differ from model to model. Most models of this type can produce detailed tree and stand information. Single-tree distance-independent models generally require a tree list as input, although functions may be available to produce a generic tree list if only stand-level data are available. Two growth and yield models, presently supported in BC, based on this approach are Prognosis^{BC} and MGM.

Prognosis^{BC}:[4] This model is based on the North Idaho variant of the Prognosis model.[5] The BC government began the process of adopting the model to make it suitable for BC conditions and species in the middle 1990s. The intent was to use it primarily for complex (e.g. uneven-aged and/or mixed species) stands. Hence, the initial effort was primarily addressed at adapting it for the south-central and southeastern parts of the province where these types of stands are more common.

Prognosis^{BC} is calibrated presently for a variety of softwood species;[6] the mountain hemlock species designation is used as a surrogate species for hardwood species. The model is capable of simulating a variety of harvesting methods and thinning regimes. Prognosis^{BC} is more accurate when projecting a stand using ground-based information; however, it can also be used to initiate a stand from bare-ground conditions. The model is comprised of several sub-models that are used to predict dbh growth, height growth, crown development, mortality, and regeneration for individual trees. Each of these sub-models may be calibrated to a particular set of conditions. The growth of small trees (i.e., seedlings and saplings with dbh < 7.5 cm) is driven by height growth predictions. Larger tree growth is driven by dbh growth predictions.

MGM:[7] The Mixedwood Growth Model (MGM) was originally developed for mixedwood stands in northern Alberta and later adapted for use in northeastern BC. The primary focus of the model is on white spruce – aspen mixtures; lodgepole pine and black spruce are also included, but less emphasis has been placed on developing relationships for those species. Input into MGM can be a tree list or stand table (for an existing stand) or an assumed dbh distribution.

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[4] More information on Prognosis^{BC} and a copy of the software can be obtained at: www.for.gov.bc.ca/hre/gymodels/progbc/index.htm

[5] This model is now known as the Forest Vegetation Simulator (FVS) in the United States. There are a number of variants that have been developed for different geographic areas as well as several ancillary components included in the FVS package that will address related issues such as certain kinds of root rot, insect attacks, and harvest scheduling. More information on FVS can be found at: www.fs.fed.us/fmsc/fvs/

[6] Prognosis^{BC} is presently calibrated for the following species: Douglas-fir, grand fir, interior spruce, lodgepole pine, mountain hemlock, ponderosa pine, subalpine fir, western hemlock, western redcedar, and western white pine.

[7] More information on MGM and a copy of the software can be obtained at: www.for.gov.bc.ca/hre/gymodels/MGM/index.htm

The model uses a sequence of scheduled events (called a crop plan) to control simulations. These events determine the source and characteristics of the stand, the growth schedule, and the timing and method of other activities like thinning, harvesting, and regeneration. Projections are made in one-year time steps until the growth schedule is completed. Output reports are computed based on all trees at or above the minimum utilization dbh. Statistics that may be provided include: stand age, total stems per ha, average dbh, average height, total basal area per ha, and volume per ha. These statistics are provided separately for coniferous and deciduous species groups.

Single-tree distance-dependent models

To build this type of model, spatial as well as attribute data are required for every tree on an area. In order to use such a model, mapped stand data could be input as a starting point. Most such models also allow different initial establishment densties and patterns to be simulated (i.e., start stand growth from bare ground). Some models of this type will also accept a stand table, together with certain stand-level values as input and generate an approximate initial spatial distribution. In this type of model, the growth of an individual tree is generally assumed to be equal to the growth of an open-grown tree of the same dimensions, reduced by some amount contingent upon the degree of competition the tree is experiencing. An estimate of the degree of competition for each tree is based on its distance from neighbouring trees and the relative sizes of the neighbouring trees compared to the subject tree.

Single-tree distance-independent models are capable of supplying very detailed information about the structure of a stand. These sorts of models can provide information on tree-to-tree competition and can monitor the effect of changes to the competitive status of the tree caused by thinning, pruning, insect defoliation, and so on. The factors that can be actively monitored depend upon how the competitive status of individual trees is determined. An example of this type of model developed and employed in BC is the model TASS (Tree and Stand Simulator).

TASS/TIPSY:[8] The Tree and Stand Simulator (TASS) model has been developed and expanded by Dr. K. Mitchell and his colleagues in the Research Branch of the BC Ministry of Forests for close to 40 years. It is calibrated for four coastal species (Douglas-fir, Sitka spruce, western hemlock, and western redcedar) and four interior species (Douglas-fir, lodgepole pine, western hemlock, and white spruce). The functional models involved are biologically-oriented, and involve height growth, branch extension, accumulation of foliage and crown expansion of competing trees, production and distribution of bole increment, suppression of height growth, and mortality. Trees are grown in a three-dimensional simulated growing space and add a shell of new foliage each year. Crowns are assumed to expand or contract asymmetrically in response to internal growth processes, physical restrictions, environmental factors, silvicultural practices, and genetic variation. TASS is not an interactive model and is not available for use by a general user, although custom runs can be arranged. Most people interact only indirectly with TASS through the

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[8] More information on TASS can be found at: www.for.gov.bc.ca/hre/gymodels/TASS/index.htm. Information on TIPSY and a copy of the software can be obtained at: www.for.gov.bc.ca/hre/gymodels/TIPSY/index.htm.

model TIPSY (Table Interpolation Program for Stand Yields).

TIPSY retrieves and interpolates yield tables from its database that were originally produced using TASS. The user may enter the following parameters into TIPSY: (1) species and regeneration method; (2) initial number of trees per ha; (3) site index or a combination of top height and age; (4) top height and number of trees per ha for existing stands; (5) genetic gain expected; (6) operational adjustment factors to account for physical and biological restrictions; (7) silvicultural treatments (pre-commercial thinning, fertilization, commercial thinning); (8) stand geographical location; (9) labour requirements; and (10) merchantability limits for total and merchantable volume. If an economic analysis is desired,[9] in addition to the above information the user must provide: (1) discount assumptions; (2) silvicultural costs; (3) harvesting costs; and (4) product prices. TIPSY can generate the following tables as a result of a run: (1) managed stand yield table; (2) stand table; (3) stock table; (4) merchantable volume per tree table; (5) stand, stock, and merchantable volume per tree table combined; (6) lumber table; (7) log table; (8) economic analysis table; (9) mortality table; (10) stand dead tree (snag) table; (11) coarse woody debris table; (12) jobs generation table; (13) variable density yield projection (VDYP) table; and (14) timber supply (TS) table.

Forest Dynamics

Where we are at today in terms of models of forest dynamics is very much influenced by earlier model developments. Terms and concepts introduced more than a century ago still affect how the forest is modelled and how management scenarios are constructed. In the first part of this section, historical approaches to modelling the dynamics of a forest will be presented and concepts pertinent to timber yield will be reviewed. This will be followed by a brief summary of the some of the approaches used for modelling forest dynamics in BC today.

Classical approaches to even-aged timber management

The major thrust of managing the forest in many locations in the world for most of this century has been to organize (schedule) the timber harvest through time. The models used were quite simple in order to keep the number of calculations, which had to be done by hand up until the last 25 years or so, to a minimum. Nevertheless, these approaches, because of their simplicity, provide insights into forest dynamics that are often obscured by the more complex computer models available today.

Although any given forest area can have portions that are managed under even-aged management schemes and other portions that are managed under uneven-aged timber management schemes, it will simplify the material if these two types of management are presented separately. Historically, timber flow was usually regulated separately for these management schemes.

[9] Base data for economic analyses are supplied by the model SYLVER (Silvicultural treatments on Yield, Lumber Value, and Economic Return). SYLVER integrates yield data from TASS with data from other sub-systems to predict wood quality, product recovery and financial return for various management regimes. More information on this model can be obtained at: www.for.gov.bc.ca/hre/sylver.

Concept of a fully regulated forest

The process of regulating the timber flow from a forest through time has been called forest regulation. Historically, regulating a forest meant bringing a forest under control. Traditionally, the target state for an even-aged portion of a forest has been a fully regulated even-aged forest (sometimes called a normal forest). Such a forest, from a timber perspective, is a constant forest. It is the ultimate result of a strict sustained yield policy that assumes that a constant flow of timber from period to period is a desired goal. Each even-aged timber type in the forest is structured so that the amount of timber available for harvest over any given period is equal to the amount of growth over that period. This implies no change in the age class structure of the forest from one period to the next once the forest is regulated.

Allowable annual cut determination under this paradigm

The ultimate aim of timber management is to produce a harvest level that meets existing demands without infringing unduly on the long-term productivity of the forest for producing timber or any other forest resource. This aim has coalesced into the concept of an allowable annual cut (AAC). Simply put, annual allowable cut is the volume of timber that can be removed, under some policy, from a given area, over a year. Considerable year-to-year variation is allowed, providing that the average over a period of years is sufficiently close to the allowable level. The allowable cut is composed of two components: (1) volumes taken at final harvest, and (2) volumes taken from thinnings. The final harvest volumes from even-aged stands may all come at one time (e.g. clear cutting), or it may be spread over a (usually short) period of time (e.g. under a shelterwood system).

In BC (and most other jurisdictions), allowable cuts are determined (i.e., set), rather than calculated. That is, AAC is not simply the result of mathematical calculations, but the result of a choice, based on a number of different inputs. Despite the fact that AAC is determined rather than calculated, mathematical formulae and models have been widely used over the years as a guide to AAC decisions. In the past few decades, the advent of computer technology has allowed rather sophisticated modelling approaches to be employed.

Historically, calculations had to be performed by hand and the approaches were necessarily simple. These approaches can be grouped into three groups: (i) area control, (ii) volume control, and (iii) hybrid approaches. The goal of these approaches was to determine harvesting levels, for an extended period of time into the future (usually at least a rotation), which would eventually lead to a fully regulated timber type (at least on paper).

(i) Area Control

The concept behind area control is very simple. Determine the area for any even-aged timber type. Then, select a rotation age (R). Every year, cut $1/R^{th}$ of the area, usually assuming the oldest timber will be harvested first. At the end of R years, a fully regulated forest would exist (in theory). The AAC would be the timber volume associated with the area harvested according to some harvesting rule (e.g. harvest the oldest stands first). If one wished to calculate the allowable annual cut for a period (e.g. 20 years), it was simply the volume associated with harvesting 20/R of the area, spaced out over the period. It was assumed that AAC would be recalculated periodically to reflect the present state of the forest.

In a fully regulated scenario, area control makes intuitive sense. The same size of land base would be harvested each planning period and the volume associated with this land base will remain constant. In a non-regulated forest, volumes would fluctuate (often widely) from period to period over, the course of converting the forest to a fully regulated state. However, the length of the conversion period to a fully regulated forest would be the shortest possible (one rotation).

(ii) Volume Control

The objective of volume control is to control the volume harvested over any period. The area associated with this volume is determined indirectly through knowing the yield of an average ha in any of the age classes harvested.

A number of volume control approaches have been used over the years. These can be grouped into categories: (1) methods based on the volume of growing stock alone, (2) methods based on increment alone, and (3) methods based on both increment and growing stock. In any of the approaches, the AAC is first calculated and then it is extended to cover the length of the planning period. Some rule (e.g. harvest the oldest timber first) is applied to determine in what age class the harvest would take place, and then the area associated with the harvest level is determined. The AAC would be recalculated periodically to reflect the present state of the forest.

As an illustration of a volume control approach, consider the formula known as Hanzlik's formula after the forester who suggested this approach for the old growth forests of the Pacific Northwest. This approach was used in BC several decades ago. The formula is:

$$AAC = \frac{G_m}{R} + I$$

where G_m is the growing stock of the mature timber (timber older than rotation age), R is the rotation age, and I is the increment of the portion of the forest that is less than rotation age. Essentially, this formula stipulates cutting a volume equivalent to the increment of the forest (primarily due to the growth of stands less than rotation age), plus a portion of the mature growing stock designed to liquidate it over the course of a rotation.

(iii) Hybrid Approaches

Hybrid approaches, as the name implies, incorporate aspects of both area and volume control. Various hybrid approaches have been applied in different jurisdictions over the years. In BC, a procedure known as the area-volume allotment check was used for a number of years. In essence, this procedure involved calculating AACs using a volume control approach (Hanzlik's formula) and then checking whether such a harvest level could be supported for a rotation based on the present inventory (area control). If the projected AACs could not be supported given the existing inventory, they were adjusted downwards until they could be supported. As was the case with the other approaches summarized above, it was assumed that the AAC would be recalculated periodically to reflect the present state of the forest.

Uneven-aged timber management

Controlled harvesting of selected trees in uneven-aged stands, and in certain even-aged stands, is referred to as uneven-aged timber management. From a management standpoint, stands that are too small to be managed under an even-aged framework would be managed as uneven-aged. This does not mean that the timber must be harvested using a single tree selection system; group selection, shelterwood, seedtree, and patch clearcut systems are also possible. It is important to differentiate between the actual silvicultural system on the ground and the general management framework.

Uneven-aged timber management has not been used extensively prior to the past decade for many of the species types found in BC. However, the present movement towards ecosystem management and maintaining biodiversity is leading towards increasing use of uneven-aged management techniques in situations where even-aged techniques have been used in the past.

An uneven-aged stand is comprised of trees with a wide range of ages. The archetypical uneven-aged stand (sometimes called an all-aged stand) has trees ranging in age (and size) from seedlings up to fully mature trees. Some uneven-aged stands will not have all developmental stages present; however, all will have several distinct age classes. By their very nature, naturally occurring uneven-aged stands are usually comprised almost exclusively of shade-tolerant tree species. Often, there are a variety of different tree species growing together. Single-species, uneven-aged stands are much less common than single-species even-aged stands.

Unlike even-aged stands, it is possible to think of a single uneven-aged stand as being regulated. The requirements of a regulated uneven-aged stand are that the size classes be represented in such proportions and growing at such rates that approximately equal annual or periodic cuts can be made indefinitely. Such a stand is often described as being balanced.

Usually, uneven-aged stands are harvested on a selection basis – either individually or in small groups. There is no equivalent concept to rotation age in uneven-aged stands. Rather, partial harvests are made at intervals known as the cutting cycle. Even if no harvesting or other intervention is made in an uneven-aged stand, the volume of the stand will eventually reach a point at which it should remain in a dynamic equilibrium, barring fire, insect attack, or other forms of catastrophic disturbance.

Decisions required in uneven-aged management

A number of decisions need to be made when managing a stand or a group of stands using uneven-aged management techniques. These decisions should be reassessed periodically.

1. *Dbh Distribution* – The dbh distribution is commonly expressed as the number of trees in each dbh class. Determining the dbh distribution also establishes the density level and the maximum tree size because of their relationship with the dbh distribution. Often the distribution is established accord-

[10] De Liocourt's constant (q) represents the average ratio between the trees in one dbh class and those in the next largest dbh class in an uneven-aged stand.

ing to a constant ratio, usually simply called q or De Liocourt's constant[10], appropriate for the tree species and products being managed. Other factors such as cutting cycle length and site quality may also influence the decision.

2. *Species Mixture* – Most uneven-aged stands support a number of species. Species composition can be influenced by selectively harvesting various species, controlling the size of openings created in the stand during harvesting, and controlling the amount of disturbance made to the forest floor, among other practices.
3. *Cutting Cycle Length* – Cutting cycle length determines the frequency of entry into a stand. Generally speaking, the longer the cutting cycle, the larger the amount of cut taken from a stand. Frequently, the over-riding determinant of cutting cycle length is the cost of harvesting the timber; the operator needs to harvest a sufficient volume of timber to cover the costs involved and provide a reasonable expectation of profit. However, too long of a cutting cycle negates some of the advantages of uneven-aged management (e.g. capturing of potential mortality).
4. *Conversion Strategy and Period* – Some (most) stands that are to be managed under an uneven-aged system do not have a suitably balanced dbh class structure when they are first brought under management. Such stands can be converted over time until a desired structure is obtained. The length of time required to do this is called the conversion period. The approach that is taken to bring about the conversion is known as the conversion strategy. The conversion period is related to the original dbh class structure of the stand. If the stand has a dbh class structure close to the one desired, then conversion can happen quickly, perhaps in as short of time as one or two cutting cycles. If the stand has a dbh class structure far from the one desired (e.g. the stand may be initially even-aged), then it will usually take at least several cycles to bring about the conversion. The conversion strategy depends, in part, on the original structure of the stand; however, it also depends on the specific tree species present in the stand and the amount of light and disturbance necessary to encourage regeneration and seedling growth.
5. *Harvest Schedule* – It is usually important that the stands being managed under an uneven-aged system are scheduled so that operating costs and the flow of timber are both relatively constant year-to-year. The forest manager must establish a reasonable harvest schedule for the first years of management. Once a cycle is established, it should remain relatively constant unless management objectives change. The scheduling is often complicated by the fact that there can be several different cutting cycles and target stand structures being used within a given forest.

Determining the harvest level

(i) Balanced Stands

If a balanced uneven-aged stand is at a sufficiently low density, little or no competition-related mortality will occur over the intended cutting cycle. Under these conditions, an amount equal to the growth can be cut without impacting appreciably on the stand structure that was present at the beginning of the cutting cycle. In order to determine the harvest level and distribution, the growth across the various dbh classes present needs to be determined.

Assume a constant dbh growth rate (*k*) across the various dbh classes, and dbh classes with a width of *m* cm, it will take $r = m/k$ years for the average tree to grow an amount equal to one dbhr class. With little or no mortality, the dbh distribution curve will shift to the right one class after r years, as shown in Figure 2. The amount that can be removed would be the difference between the two curves, shown by the grey area in the figure.

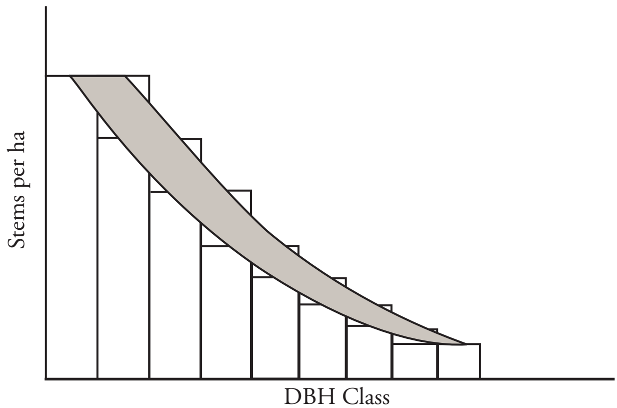

Figure 2:
Grey area represents the amount that can be removed after *r* years with constant growth in dbh across the various classes.

In order to determine how much that will be in a general sense, the relationship between adjacent dbh classes needs to be examined. In a balanced uneven-aged stand, the ratio between the number of trees in any one dbh class and the number of trees in the next largest dbh class is a constant value equal to *q*. That is, if one dbh class has *n* trees in it, the next largest class would have n/q trees, the next largest again n/q^2, and so on. This means that the logarithms of the number of stems per ha (frequency) for each dbh class will appear as a straight line if they are plotted against dbh class midpoints.

The change in frequency from any one dbh class to the next can be written as $n - n/q$. This can be expressed as a proportion of the original number of trees by dividing by *n*. Thus, if the stand is to be returned to its original structure after r years, the following proportion should be cut:

$$\frac{n - n/q}{n} = 1 - \frac{1}{q}$$

This proportion can be easily converted into a volume to be harvested, based on the average size of trees in each dbh class.

In order to generalize this formula so that it works for any length of cutting cycle, not just a cutting cycle equal to *r* years, it is first necessary to realize that a compounding discount rate (*i*) is appropriate. This rate is determined as that rate which reduces *n* trees to n/q trees over *r* years. This can be determined algebraically as follows:

$$\frac{n}{q} = \frac{n}{(1+i)^r}$$

$$\therefore (1+i)^r = q$$

$$\therefore\ i = \sqrt[r]{q} - 1$$

The proportion to cut for a cutting cycle of *t* years can be determined as:

$$\frac{n - \dfrac{n}{(1+i)^t}}{n} = 1 - \frac{1}{(1+i)^t}$$

Substituting for *i* in this formula, using the result obtained above, yields:

$$1 - \frac{1}{(1 + \sqrt[r]{q} - 1)^t} = 1 - \frac{1}{\sqrt[r]{q}^{\,t}} = 1 - \frac{1}{q^{\frac{t}{r}}}$$

This is the general formula for determining the proportion to cut in any dbh class after t years. The necessary assumptions are: (1) that it takes *r* years for an average tree in that class to grow in dbh an amount equal to the class width and (2) little or no mortality takes place. If trees from different dbh classes grow in dbh at different rates (likely the case in reality), the proportion to cut should be calculated separately for each class. If mortality is occurring, the proportion of live trees to be harvested in each class should be reduced to account for the mortality.

(ii) Unbalanced Stands

Most stands that are just being brought under uneven-aged management will not have a balanced dbh class structure. It will take a number of years (the conversion period) until such stands achieve such a structure. During the conversion period, the volume harvested will likely vary, perhaps widely, from cutting cycle to cutting cycle until the desired structure is achieved. The amount that will be harvested at the end of any cutting cycle will depend on the growth rate of the stand, the conversion strategy being followed, and the approach of the stand towards the desired dbh class structure. The length of the cutting cycle may also be varied over the course of the conversion period to facilitate the conversion. All these considerations mean that little can be said in general about how much should be harvested in any given stand, at any given point in the conversion period. Stands need to be treated individually, and a series of partial cuts planned that are appropriate for the present dbh and species structure of a stand and the structure thought to be desirable for that stand.

The initial step is to superimpose the desired size structure (dark lines) over the existing size structure (the grey histograms), as shown in Figure 3. In dbh classes where the present number of stems per ha exceeds the desired level (represented by the dark grey in the figure), some (perhaps all) of the excess could be harvested. The amount harvested must be tempered to avoid opening up the stand too much, which could encourage brush rather than regeneration of desirable species and subject the residual trees to the possibility of damage from wind.

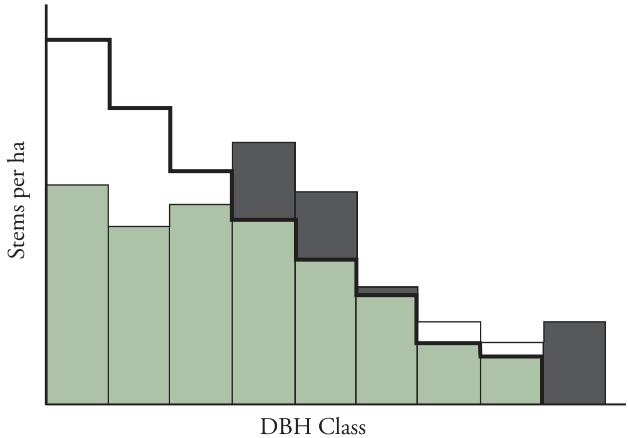

Figure 3:
An illustration of an unbalanced stand structure (depicted by the two shades of grey) versus a desired stand structure (depicted by the solid lines).

Modelling forest dynamics

Models of forest dynamics have been called by several names in the literature, depending on the use of the model and the perspective of the user; timber supply models, harvest scheduling models, and forest estate models are probably the most common. The term "forest estate models" will be used throughout the remainder of this section.

There are two basic approaches to formulating forest estate models: mathematical programming and simulation. Of the various mathematical programming approaches available, linear programming has been by far the most commonly applied in forest estate models. The remainder of this section will provide an overview of linear programming and simulation approaches to forest estate modelling and will briefly touch on spatial forest estate models.

Linear programming approaches

Many of the early applications of linear programming (LP) in forest management addressed aspects of timber harvest scheduling. Not only was this considered the major thrust of forest management in many jurisdictions at the time, but this type of problem was also quite conducive to solution using LP.

LP approaches to timber harvest scheduling and planning provide many advantages over earlier applications of area and volume control formulae. They make it easy to incorporate silvicultural prescriptions into the potential activities. The output from the LP model is a strategy for managing the forest into the future. Furthermore, the strategy is optimal for the conditions included in the model, because LP formulations are mathematically tractable.

Weaknesses of LP approaches include the fact that the cost of mathematical tractability is conformity to the assumptions required by LP (e.g. linear objective function, linear constraints). This restricts the flexibility of the model. Another problem is the absence of spatial dimensions in any operational LP model of timber supply. This is due to the fact that the problem rapidly becomes too large for solution if spatial considerations are addressed. Lastly, LP-based timber supply models can be very complex and may become almost like a black box (especially to members of the public). The strategies produced may be difficult to explain and justify. These last two weaknesses make LP formulations awkward to use in forest-level models designed to address a range of forest values in addition to timber.

(i) Type I Model Formulation

In order to set up a timber harvest scheduling problem for solution using LP, a list of the goals, issues, and silvicultural choices for the area being managed, as well as relevant economic data and inventory information, are required.

The first step is to ascertain the goal. Often it was to maximize the volume of timber harvested. The next step (and probably the most difficult) is to define the activities (decision variables). Once the activities are defined, then the objective function and the constraints can be formulated. The empirical data available (e.g. the timber types comprising the inventory, growth and yield information) will get incorporated as coefficients and right-hand-side values in these equations.

The number of activities in a Type I problem is simply the number of analysis unit / prescription combinations. In general, a decision variable X_{ij} is defined as the number of hectares of analysis unit i managed according to management prescription j. There may be many possible prescriptions for a given analysis unit. Not all of the area in a given analysis unit has to follow the same prescription; the area can be divided among several of the prescriptions. Also, there may be different sets of prescriptions for different analysis units.

Once the decision variables have been defined, the objective function can be stated. In general, it takes the form:

$$\text{Maximize } Z = \sum_{i=1}^{n} \sum_{j=1}^{m_i} V_{ij} \times X_{ij}$$

where X_{ij} is the number of ha of analysis unit i assigned to prescription j, and V_{ij} is the "value" of prescription j on analysis unit i. The units of V_{ij} must agree with the goal. For example, it could be in terms of m^3/ha if the goal is to maximize the volume harvested over the planning horizon, or it could be in terms of \$/ha if the goal is to maximize the net present value per hectare.

The nature of the problem, any special concerns of the manager, and the policies in effect, govern the form of the constraints. For a Type I model, the constraints tend to fall into the following broad classes:

Area Constraints: The purpose of area constraints is to ensure that the total area managed by all of the m_i prescriptions defined for analysis unit i does not exceed the total area in that analysis unit. There will be one area constraint for each of the analysis units.

$$\sum_{j=1}^{m_i} X_{ij} \leq A_i \qquad \text{for } i = 1,\ldots,n$$

Commodity Accounting Constraints: These constraints do not influence (constrain) the solution. Rather, they are included to handle the arithmetic involved in determining how much area and how much volume is harvested in each of the periods. Only the decision variables that involve harvesting in a given period (X^t_{ij}) are included on the left hand side of the constraint. The new variables introduced (a_t and v_t) simply denote the total area and total volume harvested in period t (of the T periods in the planning horizon). Generally, there would be two commodity allocation constraints per period within a given timber type. A timber type is a grouping of analysis units that are comprised of the same or similar species.

$$\sum_{i=1}^{n} \sum_{j=1}^{m_i} X^t_{ij} - a_t = 0 \qquad \text{for } t = 1,\ldots,T$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m_i} V^t_{ij} X^t_{ij} - v_t = 0 \qquad \text{for } t = 1,\ldots,T$$

Regulation Constraints: Normally, either the area harvested or the volume harvested in a period is regulated. The regulation constraints may be either specific (e.g. the area harvested in period t must be less than some quantity) or proportional (e.g. the volume harvested in period t must be within 10% of the volume harvested in period t-1). Specific regulation constraints are more common when area is regulated and proportional regulation constraints are more common when volume is regulated. There would be one pair of specific regulation constraint per period; hence, $2 \times T$ of these constraints for the entire problem. If there are proportional regulation constraints, there would be $2 \times (T-1)$ of them for the entire problem. If specific species types or management units are regulated individually (this is seldom the case), the number of regulation constraints required for the entire problem given above would be multiplied by the number of different groups for which regulation is required.

Specific Regulation

$$a_t \geq L_t \qquad \textit{for} \quad t = 1,\ldots, T$$
$$a_t \leq U_t \qquad \textit{for} \quad t = 1,\ldots, T$$

Proportional Regulation (for a 10% maximum allowable chage)

$$v_t \geq 0.9 \times v_t - 1 \qquad \textit{for} \quad t = 2,\ldots, T$$
$$v_t \leq 1.1 \times v_t - 1 \qquad \textit{for} \quad t = 2,\ldots, T$$

Special Constraints: Special constraints are not necessary to formulate the problem in a theoretical sense, but are often required to meet policy, budgetary, or other requirements. There are a few types of this category of constraints that are fairly common; the others tend to be specific to the analysis and jurisdiction.

(a) Ending Inventory Constraints: Because LP only optimizes over a finite planning horizon, a solution may be provided that leaves nothing to be harvested after the end of the planning horizon. In order to address this issue, the solution within the planning horizon must be linked to a desired forest structure beyond the end of the planning horizon. One way to do this is to impose ending inventory constraints. In a Type I model formulation, this means incorporating an ending inventory aspect into each of the decision variables. This is possible to do, but is not straightforward. A second way to accomplish the same thing is to have a constraint that establishes a constant level of harvest once a conversion period has passed.

(b) External or Policy Constraints: Frequently, constraints are imposed on a timber supply analysis problem to address resource concerns other than timber, budget limitations, species mixtures in the harvest, etc. These constraints can take on a number of forms. The impact of adding more and more constraints to the LP problem is that the feasible region becomes smaller and smaller. It frequently gets to be so small that there is very little difference between the best feasible solution and the worst feasible solution. The analyst ends up just trying to find any feasible solution. In such situations, some of the policy or regulation constraints have to be slowly relaxed until a feasible solution appears. This can be a time consuming process.

(ii) Operational Applications of Type I Models

The data required for a timber harvest scheduling problem consist of:

1. Inventory data – e.g. stand types, areas, ages, site qualities, current volumes, stand conditions (stocking, insect and disease presence).
2. Stand management prescriptions – a schedule of all the silvicultural and harvest activities that could take place during the planning horizon for a given analysis unit.
3. Growth and yield information – for each analysis unit / prescription combination.
4. Length of planning horizon and planning periods.
5. Primary management goal – e.g. maximize volume harvested, maximize present net worth.
6. Management constraints – e.g. volume control regulations, other policy constraints.
7. Financial data – e.g. log values, harvest costs, silvicultural costs, interest rate (necessary for present net worth).

These data are used to provide the coefficient values necessary to complete the problem formulation.

Usually, timber supply analysis problems are so large that it would take a very long time to prepare the input for computer solution. To overcome this difficulty, computer programs have been developed to prepare the input file according to some pre-defined rules that limit the scope of the activities that can be considered. These programs are known as matrix generators.

A matrix generator forms the essence of all LP-based forest estate models. In fact, it is often the matrix generator that is referred to when the model is mentioned. The user is expected to provide the matrix generator with information on the present age class distribution of the important yield classes (some limited number of these), the length and number of planning periods, the future volumes for the present yield classes, the volumes to be associated with possible future regimes (a limited number of these as well), and an operability window for each class. From this information, the matrix generator constructs the analysis units and the area and commodity allocation constraints. Additional information is required for structuring the regulation and ending inventory constraints.

The second part of a LP-based forest estate model generates the LP solution. Usually, a commercial LP package is employed. The third and final part is known as a report writer. The report writer is designed to read the output from the LP solution software and prepare an output summary, often containing tables and graphs, which is more easily interpretable than the standard LP output. However, no new information is generated and often some of the information available from the LP output (e.g. dual values, ranging) is omitted.

One of the first LP-based forest estate models to be widely used is Timber RAM (Resource Allocation Model).[11] This classical example of a Type I LP formulation was developed by the U.S. Forest Service in the early 1970s and considered for application in BC in the mid-1970s. In Timber RAM, the analysis units are defined in terms of stand types that are strata-based (i.e., scattered areas of land possessing similar timber characteristics are grouped together). Land that is to be precluded from timber harvest is deleted from the land base prior to analysis. Constraints corresponding to commitments to produce outputs other than timber are modelled as reduction in the volume available for harvest from particular stand types. This can be done in two ways: (1) reduce yields, and (2) reduce harvest flows for the first few periods. If constraints could not be represented in this way, they were ignored. Restrictions on the spatial distribution of harvests could not be handled. In other words, the solution is strategic rather than tactical – there is no indication where to cut.

(iii) Type II Model Formulation

The lack of flexibility in designing activities in Type I formulations (because of concerns over problem size) led to the development of the Type II formulation. In this formulation, analysis units are ephemeral (i.e. they exist only between the regeneration and harvest of a stand); new units are created for the next rotation. All possible combinations of rotation ages can be easily represented.

Four types of decision variables are required:

Y_{ljk} = number of hectares of yield class *k*, in analysis unit *l* in the initial inventory, harvested in period *j*.

U_{lEk} = number of hectares of yield class *k*, in analysis unit *l* in the initial inventory, that is left to form part of the ending inventory in period *E*, the end of the planning horizon.

R_{ijk} = number of hectares of yield class *k*, regenerated in period *i* and subsequently harvested in period *j*.

W_{iEk} = number of hectares of yield class *k*, regenerated in period *i*, that is left to form part of the ending inventory in period *E*, the end of the planning horizon.

Areas regenerated in one period are either harvested in another period or left as ending inventory. Silvicultural treatments can be incorporated by using a subscript to represent various silvicultural prescription sequences.

In a Type II problem formulation, the decision variables can be viewed as pathways or flows. There would be a number of networks working in parallel in a realistic problem, with each network representing a different yield class. The LP solution provides values for each of the decision variables, indicating the number of

[11] Navon, D.I. 1971. Timber RAM – a long-range planning method for commercial timberlands under multiple-use management. USDA Forest Service, Res. Pap. PSW-70. 22 pp.

ha traveling down each pathway to provide an optimal solution.

In terms of problem formulation, the Type II model differs from the Type I model in two major ways: (1) the decision variables are defined differently and (2) an additional set of constraints is required for each period and timber type. The decision variables for the Type II formulation were defined above. The additional constraints are known as transfer row constraints because they are used to govern the flow of area into and out of each planning period (node). The basic idea is that the land area that flows into a node (i.e., a harvest/regeneration activity in a given period) must flow out of the node (i.e., be available for harvest in some subsequent period or form part of the ending inventory).

The Type II model takes the following mathematical form:

Objective Function:

$$\text{Maximize} \qquad Z = \sum^{l} \sum^{j} \sum^{k} V_{ljk} Y_{ljk} + \sum^{j} \sum^{k} V_{ijk} R_{ijk}$$

Constraints:

Area: One constraint required for each yield class and analysis unit. (Similar to Type I models).

$$\sum^{l} Y_{ljk} + \sum^{i} R_{ijk} - a_{jk} = 0 \qquad \text{for } j = 1,\ldots,T \text{ and } k = 1,\ldots, K$$

Transfer Row: One constraint for each period and yield class.

$$\sum^{l} Y_{ljk} + \sum^{i} R_{ijk} = \sum^{j} R_{ijk} + W_{iEk} \quad \text{where j on the LHS = i on the RHS}$$

$$\text{for } j = 1,\ldots,T \text{ and } k = 1,\ldots, K$$

Commodity Allocation Constraints: One for each commodity (e.g. area, volume), period and yield class. (Similar to Type I models.)

Area:

$$\sum^{l} Y_{ljk} + \sum^{i} R_{ijk} - a_{jk} = 0 \qquad \text{for } j = 1,\ldots,T \text{ and } k = 1,\ldots, K$$

Volume:

$$\sum^{l} V_{ljk} Y_{ljk} + \sum^{i} V_{ijk} R_{ijk} - v_{jk} = 0 \qquad \text{for } j = 1,\ldots,T \text{ and } k = 1,\ldots, K$$

Regulation Constraints: One pair for each of the T periods (specific) or one pair for each T-1 period (proportional). The constraints may regulate either volume or area. (Similar to Type I models.)

Specific Regulation for area

$$\sum_{k} a_{lk} \geq L_{t} \qquad for \quad t = 1,\dots, T$$

$$\sum_{k} a_{th} \leq U_{t} \qquad for \quad t = 1,\dots, T$$

Proportional Regulation for volume (10% allowable change)

$$\sum_{k} v_{tk} \geq 0.9 \sum_{k} v_{t-1,k} \qquad for \quad t = 2,\dots, T$$

$$\sum_{k} v_{tk} \leq 1.1 \sum_{k} v_{t-1,k} \qquad for \quad t = 2,\dots, T$$

Specific Constraints: As in Type I formulations, these types of constraints are specific to the problem context. The one notable difference is that ending inventory constraints are easily handled in Type II models because there are specific variables that represent the ending inventory levels.

(iv) Operational Applications of Type II Models

The first model developed to make use of the Type II formulation was MUSYC (Multiple Use Sustained Yield Calculator).[12] It was developed in the mid-1970s under the sponsorship of the US Forest Service. Like Timber RAM, it is comprised of three parts: (1) a matrix generator, (2) external LP solution code, and (3) a report writer. When MUSYC is mentioned, usually it is the matrix generator that is meant. MUSYC has been used operationally in a number of different jurisdictions over the years, including BC.

MUSYC has improved constraint capacity and reporting over Timber RAM. It increases the emphasis on sub-forest constraints and reports by defining forest-wide strata. (However, these are not geographically defined areas like watersheds.) Like Timber RAM, MUSYC takes a strata-based approach to the analysis. This means there is no recognition of geographic areas important to non-timber uses. Even for timber, a strata-based approach does not recognize economic accessibility, harvesting feasibility, etc. In actuality, the use of "multiple use" in the model title is a misnomer; MUSYC is very much a timber-oriented model.

As the need for a broader planning perspective was recognized, a model was developed to address multiple-use issues explicitly (FORPLAN – FORest PLANning model).[13] This model is a true forest planning model, as opposed to strictly a timber planning model. It was designed to provide an analytic structure that could represent the multiple-use interactions that represent the range of choice in forest output. It also kept enough of the usual timber scheduling characteristics to be able to specify efficient sustainable harvest schedules within a broader multiple-use context.

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12 Johnson, K.N. and D.B. Jones. 1979. A user's guide to multiple use – sustained yield resource scheduling calculation (MUSYC). Dept. of Forestry and Outdoor Recreation, Utah State University, Logan, Utah.

13 Johnson, K.N., D.B. Jones and B.M. Kent. 1980. Forest planning model (FORPLAN) – User's guide and operations manual. USDA Forest Service, Land Use Planning Systems Application Unit, Fort Collins, CO.

FORPLAN started with the basic analytic structure of MUSYC, but added a series of improvements by recognizing:

1. land other than commercial timberland;
2. choices other than harvesting and growing timber;
3. outputs other than timber;
4. values for outputs other than timber;
5. geographic areas within the forest for reports and controls; and
6. geographic areas within the forest for allocation decisions.

The output from FORPLAN is a land allocation strategy.

(v) Allowable Cut Effect

The allowable cut effect (ACE) is an immediate increase in harvesting level as a result of performing silvicultural treatments that are expected to bring about future returns in terms of yield increases. ACE has been the subject of much debate over the past 30 years. A brief summary is provided here because it is intimately related to an LP-type of constrained flow problem.

ACE provides one way of showing an immediate financial return from a silvicultural treatment. Since present levels of harvesting (usually in an unmanaged forest beyond rotation age) are generally limited by projected timber supply in managed forests of the future (often of younger age and with less volume per ha), any activities that will increase future yield can result in higher cuts today, under a sustained yield policy.

Opponents to the use of ACE point out that it is an inherent artifact of the sustained yield concept. If a sustained yield policy does not exist, there is no ACE. This is the basis for the dislike by many economists. Another difficulty with ACE is that it ignores risk (both biological and economic). The use of ACE implicitly assumes that the silvicultural treatments scheduled in the analysis will actually be implemented and that they will yield the higher volumes predicted.

(vi) Incorporating Non-Timber Forest Values in LP Models

The roots of LP-based forest estate models are in timber harvest scheduling. These models worked well as strategic planning tools for this purpose, modelling forest dynamics over large areas and long time spans (e.g. 100 to 200 years). They have been less successful as aids in tactical timber harvest planning, which is concerned with locating areas to harvest over relatively short time frames (e.g. < 20 years). Part of the difficulty in using these models as tactical aids relates to their non-spatial nature (i.e., stands are generally grouped into strata and lose their spatial orientation).

Implicit in the orientation of most LP-based forest estate models is the idea that the focus of the modelling exercise is to optimize some aspect of timber management. Other forest resources are treated as constraints to the timber management within the model or simply excluded from the land base prior to modelling. This approach is not an absolute necessity (e.g. FORPLAN is a notable exception), but it does serve to keep the models relatively simple to use and understand.

There have been numerous attempts at using mathematical programming techniques other than LP to solve forest estate models documented in the literature, most notably goal programming and mixed integer programming. However, these methods generally have not seen widespread use in operational settings. This is partly a result of model complexity and partly related to heavy information demands in order to run the model.

The difficulty of explicitly incorporating forest resources other than timber in LP-based forest estate models has been one of the factors that has led to the decline in the use of these models over the past few decades.

Simulation approaches

The first simulation-based models of forest dynamics appeared in the early to middle 1960s. Like their LP counterparts, these models were designed primarily to address issues surrounding the flow of timber supply from an area over time. However, the flexibility inherent in simulation made it easier to adapt these models to consider other forest resources besides timber than was the case with LP approaches.

Simulation approaches to timber harvest scheduling and planning allow great flexibility in terms of model structure. Equations need not be linear nor conform to another other structural restrictions. The cost of this increased flexibility is that no management regime can be determined to be best, mathematically. In fact, a management regime is one of the inputs to a simulation model, whereas it is an output from a LP model. Based on the output provided by the simulator, the model user modifies the management regime until an output is achieved that is considered to be acceptable.

The conceptual approach taken by simulation models can be easily explained, preventing the model from being thought of as a "black box". This allows the results of the simulation modelling to be more easily understood by individuals not actively involved in the modelling process.

The flexibility inherent in simulation approaches makes it easier to incorporate forest values in addition to timber into the modelling framework than is the case with LP-based approaches. While there are no theoretical restrictions on the number of such values that can be incorporated, there are a number of practical restrictions.

(i) Application of Simulation to Timber Harvest Scheduling Problems

Over the years, numerous simulation models have been developed to aid in timber harvest scheduling. These models are difficult to describe in general terms because simulation approaches do not have to conform to any rigid mathematical form; hence, many different structures can be used. Nevertheless, a few generalizations can be made.

An inventory of the existing timber resource, usually summarized in the form of area by yield class and age class, forms the basis for describing the existing forest. Stands need not necessarily be aggregated into such broad classes. It is possible to keep track of each stand individually; however, the model rapidly becomes very large, and perhaps impossible to work with, if the area of the forest is extensive. At least one yield function (yield curve or yield table) is assigned to each of the existing yield classes. The same function or other functions are assigned to the area in each yield class after it is harvested. The purpose of the yield functions is to assign volumes to the land area, both now and in future years, as the forest is projected into the future.

The final input to a simulation-based timber harvest scheduling model consists of an initial management strategy, usually comprised of a number of targeted silvicultural regimes, a harvesting rule, and a harvest level. The silvicultural regimes are normally devised for a particular yield class and age range. Often, a maximum (and sometimes minimum) area to be treated each period is given. The harvesting rule governs how stands (or aggregations of stands) are selected for harvesting. Often a simple rule such as "oldest first" is used, but many more elaborate rules are possible as well. The harvest level is the quantity of timber that is targeted for harvesting in any period. This level is often held constant from period to period, but that need not be the case. The harvest level initially set seldom coincides with other aspects of the management strategy (i.e., it is either too high or too low).

Once the initial forest is described, yield functions assigned, and an initial management strategy set, the simulation phase of the model begins. In each period of the simulated planning horizon, the harvest specified in the harvest level is taken according to the harvesting rule, silvicultural regimes are applied as appropriate, and then the forest is grown for a period. This process is continued until either the forest is exhausted by over cutting or the end of the planning horizon is reached. Usually, descriptive statistics regarding the condition of the forest are output for each period.

Once the simulation is complete, an evaluation of the run is made. This evaluation may be done by the user or it may be performed automatically. The easiest automatic evaluation is whether or not the harvest level coincides with the management strategy. The highest sustainable harvest level can be found automatically using a binary search procedure. A binary search procedure begins by finding a level that is sustainable and one that is not. It then tries a harvest level that is midway between these two. If that level is sustainable, then the midpoint between that level and the lowest non-sustainable level is tried. If that level is not sustainable, then the midpoint between that level and the highest sustainable level is tried. This procedure is continued until the highest sustainable level for a given management strategy is found.

Evaluation of the management strategy is a difficult process to automate. Usually the model user will explore a number of different management strategies. These will then be evaluated according to some criteria, and the best one(s) selected. There is no guarantee that the strategy selected is the best overall strategy for the criteria used; it will simply be the best of the ones examined.

Simulation models are widely used in Canada today to assist in sustainable forest management planning. The model with the oldest lineage is FORMAN (FORest MANager), originally developed for New Brunswick in the late 1970s and subsequently revised several times. The model presently used in BC for timber supply analyses (FSSIM – Forest Service SIMulator) has some architectural linkages back to FORPLAN.

(ii) Incorporating Non-Timber Forest Values

As was the case for LP approaches, the roots of simulation-based forest estate models are in timber harvest scheduling. However, the flexibility of simulation approaches makes it easier to incorporate non-timber forest resources than is the case with LP. Any forest attribute (characteristic) that can be quantified, and that can be related to the forest structure that is being projected through time, can be incorporated in a simulation approach.

It is also much easier to incorporate stand locations (spatial attributes) within a simulation approach than within a LP (or any other mathematical programming) approach. Because simulation models are not solved to provide an optimal solution, problem size becomes much less of a concern.

While there are not any theoretical limits to the number of value attributes that can be incorporated into a simulation model, there are practical limits. Each attribute needs to be quantified in relation to the forest structural components that are being projected by the model. If this is to be done in a meaningful way, it requires considerable knowledge about the relationship between the attribute and the forest structure. Such knowledge is presently lacking for many potential attributes. Scale also imposes problems. Forest-level simulation models usually operate at the scale of a group of stands with similar characteristics (non-spatial models) or single stands (spatial models). Certain attributes that may be of interest to forest managers (e.g. snags) may be best modelled at finer levels of resolution. Finally, individuals can only comprehend a limited number of attributes. If too many (likely) conflicting attributes are provided in a model's output, this can serve to confuse the forest manager (and the public) by obscuring important trends with unimportant details.

Spatial models

The modelling approaches summarized thus far are applicable to quite large forest areas over long periods of time providing the user is willing to group large numbers of individual stands of trees into a much smaller number of classes. These approaches are still useful in forest management today, especially for strategic decisions like determining the AAC for a large region. However, many concerns that are important to forest managers (e.g. cut block size, green-up periods, wildlife corridors) are spatial in nature. Models that incorporate spatial locations are a useful tool for the forest manager to use in designing management schemes that are sensitive to these concerns.

(i) Overview

A number of spatially sensitive forest estate models exist. These models incorporate a range of approaches, but most involve some form of simulation. Mixed integer programming models have been developed, but only work for areas containing a limited number of stands because of problem size restrictions. Simulation approaches also encounter size restrictions, but these usually occur at a much larger number of stands than is the case for mixed integer programming (e.g. thousands to tens of thousands of stands compared to hundreds to thousands of stands in mixed integer programming models).

All spatially sensitive simulation models incorporate one or more search procedures to assign treatments to various spatial units. The search procedures used in spatial models look for solutions (schedules) that meet a set of rules for assigning treatments to units (stands) which are sensitive to spatial relationships. For example, if green-up rules are incorporated, harvesting in adjacent units might be restricted for a certain number of periods once a particular unit is scheduled for harvesting. Some search procedures involve random components (e.g. units which are to be harvested at some point in time may be selected randomly from a list of eligible units). Models that involve random searches are often run a large number of times and the "best" solutions are saved for perusal by the user. Other search procedures employ deterministic rules, so that the same set of starting conditions and restrictions always leads to the same solution.

Spatially sensitive forest estate models can be used for a number of purposes. For example, they can be used as an aid in producing a tactical plan for a given area which forms a portion of a larger unit for which an AAC is determined. A tactical plan is generally short term (e.g. less than 20 years) and specific which respect to treatment timing and location. It is common in such cases that the harvest level, thought to be available from strategic analyses conducted using non-spatial models, would need to be reduced to account for various spatial considerations. The reduction that is necessary can be used as feedback to the strategic planning process to assist in determining appropriate harvest levels in future analyses. If the forest unit for which an AAC is to be determined is small enough, spatial forest estate models can be used to produce both strategic and tactical analyses that are compatible with one another. Spatial forest estate models can also be used in policy analysis/design, since the potential impacts of various policies which govern spatial accessibility can be assessed prior to actual implementation.

(ii) Brief Summary of ATLAS

ATLAS is a spatial model that has been applied in BC in recent years. ATLAS is presently imbedded in a suite of application software known as FPS (Forest Planning System), designed to facilitate its application. This model has been developed over the last decade by a team of researchers at the University of British Columbia led by Dr. J. Nelson. The model is briefly described below; more detail can be obtained at: www.forestry.ubc.ca/atlas-simfor/.

ATLAS is a simulation-based, spatial, forest-level planning model designed to schedule harvest units according to a wide range of spatial and temporal constraints. As a starting point, the user must have a spatial data set which includes the proposed harvest units. Total resource plans (sometimes referred to as total chance plans in BC) that spatially define potential harvest units and road networks are a prerequisite to running ATLAS.

Figure 4 shows the general representation of the forest and an overview of the model. The forest is first partitioned into polygons (representing potential harvest units, reserves, and non-forested areas). Polygons are the critical elements of the model. While they can be aggregated into larger units, such as zones and cliques, they cannot be split into smaller units. Each polygon has a number of attributes (e.g. age, stand group, reserve status) that are essential for forest level modelling. Silviculture treatments and growth and yield data are applied to each polygon through the stand groups. Polygons also provide a link to road networks (optional).

Polygons may be assigned to zones and cliques used to establish harvest priorities and to which constraints can be applied. A polygon must belong to one and only one zone; however, it may belong to none, one or several cliques. While constraints can be applied to both cliques and zones, harvest priorities can only be applied to zones. At the next spatial level are access units, which are groupings of zones. The access unit typically covers a large portion of the forest (often the entire forest), and can be used to set harvest priorities and as an area to which constraints can be applied. A zone must belong to one and only one access unit.

Project and run parameters (time horizon, planning period, harvest flow

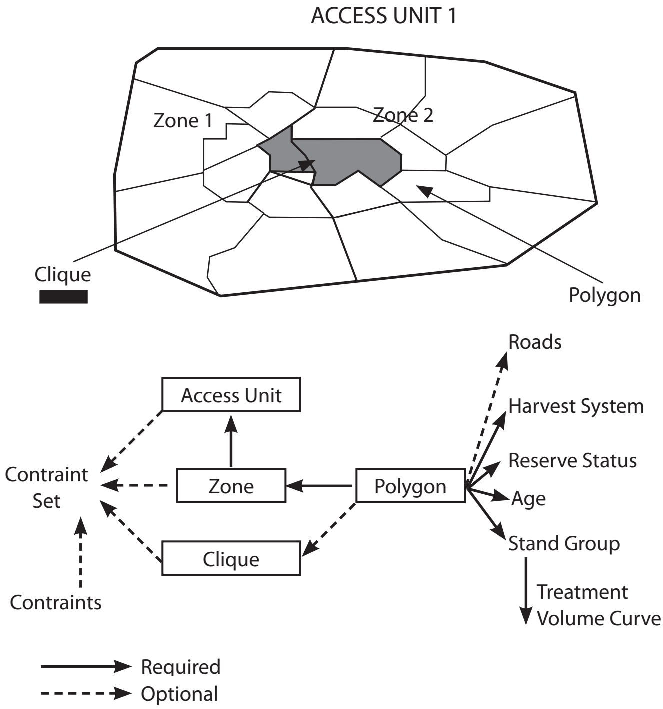

Figure 4: An overview of the ATLAS model.

targets, etc.) need to be defined for each simulation. Constraint sets (collections of individual constraints) can be defined and applied to cliques, zones and access units. Constraints include adjacency/green-up rules, seral stage constraints, within block reserves, and equivalent clearcut area rules for hydrology.

ATLAS uses the following procedure to simulate a harvest scenario:

1. Go to the access unit with the highest harvest priority and which is eligible for harvest. If no access units are eligible, go to step 6, otherwise go to step 2.
2. Go to the zone within this access unit that has the highest harvest priority, and which is eligible for harvest. If no zones are eligible for harvest, close this access unit, and return to step 1, otherwise go to step 3.
3. Go to the polygon within this zone that has the highest harvest priority, and is eligible for harvest (not reserved, meets minimum age requirement, not excluded due to adjacency, etc.). If no units are eligible, close this zone, and go to step 2, otherwise go to step 4.
4. Temporarily harvest the block and check all constraints that have been applied to relevant cliques, the zone, and the access unit. If successful, go to step 5. If unsuccessful, reject the temporary harvest and pursue the following three possibilities:

- if the polygon fails a clique constraint, make the polygon ineligible for harvest and return to step 3.
- if the polygon fails a zone constraint, close the zone and return to step 2.
- if the polygon fails an access unit constraint, close the access unit and return to step 1.

5. Permanently accept the harvest of this polygon. Update attributes and eligibility of polygon, zone, and access unit resulting from this harvest. Apply the harvest volume to the periodic harvest target. If the harvest target has been met go to step 6, otherwise return to step 3.
6. Summarize and report harvest statistics for this period. If the planning horizon has been reached, stop, otherwise age the forest by one planning period, update attributes and constraints, and return to step 1.

If desired, an optional road network analysis can be run following the harvest schedule. Briefly, ATLAS examines each periodic harvest schedule, and determines which road links need to be constructed or kept active in order to access the polygons scheduled for harvest.

Timber Supply Analysis in BC[14]

Background

Timber supply is a measure of the potential availability of timber from a forest through time. The extent and productivity of the area available for timber production (the timber harvesting landbase), economic, environmental, and social factors all impact on where, when, and how much harvesting can take place. Analysis of timber supply is shaped by the legal framework that governs forest management on Crown lands in BC. This framework is comprised of The *Forest Act*, The *Forest Practices Code of British Columbia Act*, the new *Forest and Range Practices Act*, the *Ministry of Forests Act*, and the *Range Act*.

Timber supply analysis explores the timber supply impacts of existing and potential forest management activities and various harvesting levels using appropriate forest-level and stand-level models on a specific forest area. These analyses are used to support a variety of planning activities, including land-use planning, forest management and silvicultural planning, and determination of the AAC.

Timber supply analyses are used to support land-use planning by enabling assessments of the extent to which each proposal or option meets specified management objectives under specified forest policies and practices. The timber production potential of different forest areas are limited by different factors. Timber supply analyses can be used to explore forest-level impacts of various silvicultural interventions, designed to modify some of the limiting factors. In terms of AAC determination, timber supply analyses are used to assess the sensitivity of timber supply to alternative forest management practices and uncertainty in the data.

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[14] The material in this section is condensed from material provided at the Ministry of Forests website: www.for.gov.bc.ca/hts/tsr.htm

Allowable Annual Cut determination

AACs are determined periodically (generally every five to ten years) by BC's Chief Forester, for the major public forest management units in the province (Timber Supply Areas – TSAs and Tree Farm Licences – TFLs). Determining an AAC is a complex process where the Chief Forester considers a number of factors, including public input, timber supply analyses, and the government's social and economic objectives. Specifically, *Section 8* of the *Forest Act* requires the Chief Forester to consider:

- the rate of timber production that may be sustained from the area;
- the short- and long-term implications to the province of alternative rates of timber harvesting from the area;
- constraints on the amount of timber produced from the area due to use of the forest for purposes other than timber production;
- the nature, production capabilities, and timber requirements of established and proposed processing facilities;
- the economic and social objectives of the Crown for the area, the region and the Province, as expressed by the Minister of Forests; and
- abnormal insect or disease infestations, and major salvage programs planned for the area.

Generally, the AAC is based on a transition strategy that will move current harvest levels to a long-term harvest level. This may result in a decrease in present harvest levels, an increase in present harvest levels, or essentially a steady state, depending upon the biological and social characteristics of the forest management unit.

There are five basic steps in a timber supply analysis made in support of an AAC determination.

1. *Categorize the landbase.* The forested land in an analysis unit is separated into area available for timber harvesting (the timber harvest landbase) and area not available or inappropriate for timber harvesting.
2. *Project growth and yield.* Stand growth and yield are projected for each stand based on current management. These projections are represented as yield curves, which show certain stand characteristics as a function of age.
3. *Identify management activities and requirements.* Current management activities are identified and the amount, timing, and location specified.
4. *Model timber supply based on current management.* A forest-level simulation model (FS-SIM) is used to simulate the timber supply under the current management regime. The simulation results are evaluated by assessing certain managerial outputs (e.g. volume harvested, area treated) and residual forest characteristics (e.g. area in each age class) for each decade of the simulation.
5. *Run sensitivity analyses.* These analyses are designed to evaluate sources of uncertainty in the data and the impact of managerial assumptions. Factors that most affect analysis results are highlighted to indicate where more caution is required in interpreting results and to help identify where additional information/data might be most helpful.

Timber supply reviews

The timber supply review program in BC is intended to periodically provide current assessments of timber supply in each TSA and TFL in the province. Timber supply analyses are used to assess how current forest management practices are anticipated to affect timber supply over time. They are also used to examine possible impacts of changes to forest management practices and data uncertainties. The information gathered by a timber supply review is used by the Chief Forester in support of AAC determinations.

For TSAs, the timber supply review consists of a four-step process:

1. *Preparation of a data package.* Information on the forest resources inventory and current practices in the TSA is complied, summarized and documented in a data package. Various stakeholders are given an opportunity to review data assumptions and any modifications required are made.
2. *Preparation of the timber supply analysis report and public discussion paper.* Timber supply is projected over a 250-year period. A base case forecast is included that is intended to illustrate the long-term effect of current forest management on timber supply. The analysis report also includes:
   - a description of the environment and ecology of the area;
   - a description of the communities and industries in the area;
   - a description of the timber harvesting and processing industries that rely on timber from the area;
   - an assessment of current timber flows and employment conditions; and
   - an assessment of the socio-economic impacts of adjusting the AAC. The technical report is summarized in a public discussion paper and both are released for public review and comment.
3. *Public review.* Meetings are held with interested parties during a 60-day public review period. Occasionally, open houses may be held in affected communities. All public input is collected, summarized, and documented, provided to the Chief Forester, and subsequently released to the public once a new AAC has been announced.
4. *Preparation of an AAC rationale statement and summary of public input.* The reasons for the AAC determination by the Chief Forester are outlined in a rationale statement. The rationale statement is released to the public together with the summary of the public input.

Information on the most recent timber supply review for specific TSAs can be found at: www.for.gov.bc.ca/hts/tsr.htm

For TFLs, the process for management plan approval and AAC determinations involves five steps:

1. *TFL management plan review.* The government conducts a review of the current management plan and provides the licensee with comments on the plan, the licensee's performance relative to the current plan, and a list of the guidelines currently in effect. The location(s) and time(s) for the draft management plan public review may also be specified.

2. *Timber supply analysis information requirements may be requested.* The government may require the licensee to provide other readily available information considered relevant to the assessment of timber supply, along with the usual timber supply analysis information package.
3. *Development of the information package and draft management plan.* The licensee must first submit to government a timber supply analysis package including information, assumptions and the approach that will be used in conducting the timber supply analysis. The government will provide the licensee with a letter either accepting or rejecting the assumptions and methodology proposed. Once it has been accepted, a draft management plan is advertised and referred. The purpose of this plan is to specify management objectives and strategies for achieving those objectives on the TFL. The draft plan provides an opportunity for the public and government agencies to review and comment on the proposed objectives and strategies.
4. *Prepare the timber supply analysis and twenty-year plan.* The timber supply analysis provides information to the Chief Forester regarding the short- and long-term timber supply forecasts that will be considered in determining the AAC. The twenty-year plan is a non-operational plan that must be accepted by the local District Manager for the Ministry of Forests. Once accepted, it will also be considered by the Chief Forester in the AAC determination. The plan outlines the ability to locate areas for harvest over the 20-year period, given the constraints included in the timber supply analysis.
5. *Development of the proposed management plan and determination of the AAC.* The licensee develops a management plan for the Chief Forester's approval. The plan is comprised of the objectives and strategies for managing resources in the TFL area, and incorporates comments from various government agencies and the public where appropriate. The plan also includes the accepted information package, the timber supply analysis, and the twenty-year plan. The Chief Forester then either approves (with or without conditions) or does not approve the plan. If approved, the Chief Forester determines the AAC and provides reasons for this determination in a rationale statement.

Information on the most recent timber supply review for specific TFLs can be found at: www.for.gov.bc.ca/hts/tsr.htm

REMOTE SENSING, PHOTO INTERPRETATION AND PHOTOGRAMMETRY

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REMOTE SENSING, PHOTO INTERPRETATION AND PHOTOGRAMMETRY

Introduction

Remote sensing is the acquisition of data from airborne or spaceborne platforms and its subsequent interpretation. The data are either in the form of aerial photographs or recordings on magnetic tape. Aerial photographs are obtained via camera-film systems whereas tape data are obtained by electro-mechanical scanners. Photo interpretation involves three phases; (1) photo reading, (2) photo measuring (photo-grammetry) and (3) answer deduction. Photo reading means using the photographs as simple tools to recognize familiar objects such as roads or trees. Photo measuring (photogrammetry) means using the photographs to obtain measurable data such as tree heights, crown diameters or topographic contours. Answer deduction means using the photographs to derive answers to questions relating to tree species, land-form type, tree condition and other items which cannot be directly read or measured on the photographs.

Remote sensing and photo interpretation are important tools in forest management. Used properly, they can economically and reliably provide information to inventory and/or monitor forest resources, vegetation condition, ecology, surficial geology and soils, land use, etc. The role of remote sensing is to reduce or replace, if possible, costly and time-consuming ground surveys. Ground surveys can then be used to obtain ancillary information not available to photo interpretation (e.g. tree age). Remote sensing and photo interpretation should be an integral component of forest resource management. Basic principles are presented in the following section along with techniques for their application to forestry. More specific and detailed information can be found in the large variety of reference texts which are cited at the end of this chapter.

Aerial Photographs

Film formats and camera types

The most common photo size is 23 x 23 cm (9 x 9 in), obtained with a precision mapping camera. The BC government and most aerial survey firms use this type of camera. Reconnaissance cameras are used for specialized purposes such as obtaining large-scale photos taken from very low altitudes from fixed-wing aircraft or helicopters. Two cameras are used with a fixed-based between cameras to facilitate photogrammetric calculations. The film size for the reconnaissance cameras is usually 70 mm.

Kinds of photographs

Vertical: The camera axis is pointing vertically downward (i.e. it is perpendicular to the ground).

High Oblique: The camera axis is not pointing vertically downward. There is sufficient tilt so that the camera view shows the horizon.

Low Oblique: The camera axis is not pointing vertically downward, but the horizon does not show in the photograph.

Most aerial photographs are vertical and, unless otherwise specified, aerial photograph implies vertical aerial photograph.

Films and filters

Four common types of aerial films and five common filters used in aerial photography are depicted schematically in Figure 1. Although black and white panchromatic films are used most often in photogrammetric applications, photographs from colour and colour-infrared films are best for photo interpretation, particularly in forestry.

1. **Black and white panchromatic film** is used mainly for photogrammetric and precision mapping purposes. The spectral sensitivity spans the visible spectrum. Selective use of filters on black and white films will permit "multispectral" photos to be obtained. For example, a Wratten 58 (green) filter with black and white pan film is used to obtain a green spectral region photograph (Figure 1).

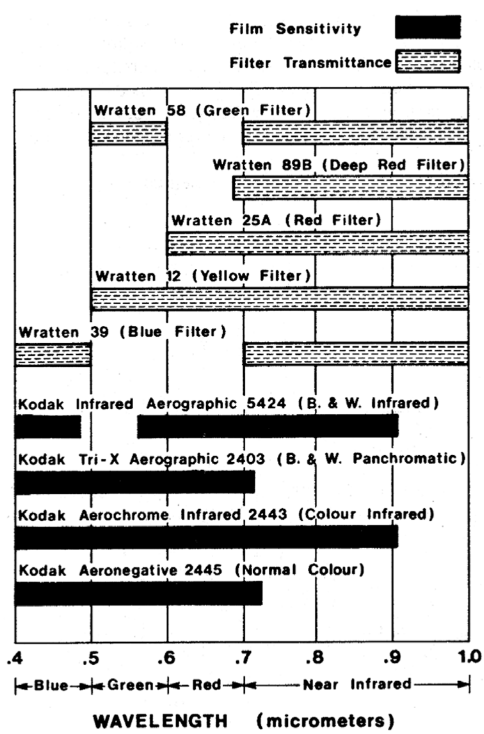


Figure 1: Four common types of aerial films and five different types of filters.

2. **Black and white infrared film**. Sensitising salts have extended the sensitivity of this film into the near-infrared (0.7 to 0.9 micrometers). Although the sensitivity of the film spans the visible spectrum as well as the near-infrared, sensitivity in the green spectral region (0.5 to 0.6 micrometers) is very low. The film is used with a deep red filter (Wr. 89 B) to give "extreme contrast" photos. Such photos have improved haze penetration because the filter eliminates green and blue wavelengths, where scattering of light predominates. On extreme contrast photos conifers appear as dark tones, whereas hardwoods appear as light tones. When used with a red filter (Wr. 25 A), "infrared" photos are produced. Although they are not as high in contrast as those taken through a deep red filter (Wr. 89 B), good haze penetration is still obtained. Near infrared sensitive films are NOT sensitive to thermal energy.

Normal-colour films

Normal-colour films are tri-emulsion films that have three dye-forming layers which are sensitive to blue, green, and red wavelengths. In positive transparency films (e.g. Kodak Ektachrome Aero, Type 2448), three dyes (yellow, magenta and cyan) are formed after reversal development. These dyes act to subtract light (Figure 2). Positive transparencies are viewed with transmitted light (i.e. on a light-table), and in normal-colour photos, the dyes act to subtract light to give objects a "natural" colour.

Subtractive Colours

(effects seen when white light is viewed through coloured filters)

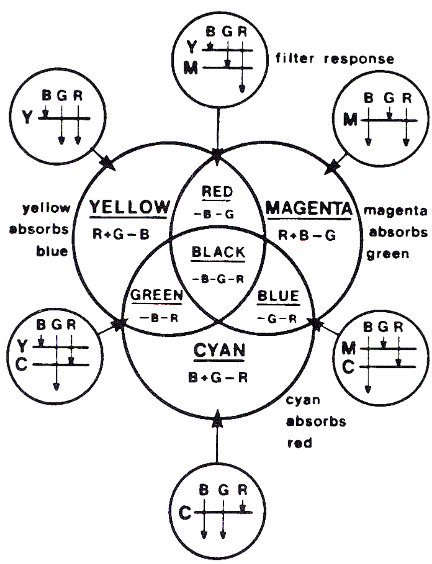


Figure 2:
There are three primary subtractive colours or dyes, which when viewed in combination will subtract all visible light. The three primary subtractive dyes are yellow, magenta and cyan. These diagrams are the basis for colour rendition in colour transparencies.

Normal colour films also come in negative format, (e.g. Kodak Aero-Negative film, Type 2445). After exposure, the film is developed to a negative from which positive paper prints are produced. Positive transparencies have a finer resolution and sharper image detail than do positive paper prints. However, prints are easier to use in the field.

Colour-infrared film

Kodak Aerochrome Infrared film, 2443, is also known as colour-infrared film, false-colour film, and camouflage detection film. The dye-forming layers are sensitive to green, red, or near-infrared wavelengths. Since all dye-forming layers are sensitive to blue light, the colour-infrared film must be used with a yellow, or minus-blue filter (Wr. 12) to eliminate the blue light. After reversal development, three dyes are formed (yellow, magenta and cyan). When viewed with transmitted light, the dyes act to subtract light (Figure 2) and consequently show images in false colours. For example, green leaves appear reddish or magenta in hue. Specific interpretation details are discussed later in this chapter. Colour infrared film does NOT respond to thermal energy.

Filters

Filters are used to either selectively transmit or absorb specific wavelengths of light. The spectral transmissions of five common filters are shown in Figure 1.

Colour compensating filters (i.e. "CC" filters) are also used to selectively transmit or absorb certain wavelengths. When used with colour films they serve to shift the resulting colours. For example, a CC20M (magenta) filter used in addition to a Wr. 12 filter will shift the colours in colour-infrared photographs towards the yellow. Such a yellow shift is desirable for tree species identification and tree condition assessment. Colour shifts of common colour compensating filters are given in Table 1.

Table 1: Colour shifts induced in colour films by colour compensating (CC) filters (after Fritz, 1967).

Colour compensating filter	Colour absorbed	Shift in film colour balance (adds more)
cc magenta (R + B)	green	yellow
cc blue	red, green	red
cc cyan (B + G)	red	magenta
cc red	blue, green	yellow
cc green	blue, red	magenta
Corning 3966	n-1r	cyan
cyan – Corning 3966	red, n-1r	blue

Taking aerial photographs

All aerial photographic firms follow the specifications provided by the Interdepartmental Committee on Aerial Surveys (ICAS) when taking government contracted aerial photographs. These specifications have been developed over a long period of time and are designed to provide the best possible mapping photographs. A contract specification "to follow ICAS specifications for mapping photography" will ensure good photos and all photos will be within the limit of tolerance for tip, tilt, crab, draft, forward overlap, lateral overlap, sun angle, time of day, cloudiness, and exposure.

The purpose of the photo mission will dictate time of day, season of the year and film type. For topographic mapping, consideration should be given to the effect of ground cover; the leafless season is preferred by many photogrammetric firms. For tree condition assessment, the season may vary from spring to fall, again dependent on the purpose of the photo mission.

Scale

An important characteristic of a photograph is its scale. Scale relates distances and areas measured in the photograph to corresponding distances and areas measured on the ground. Scale is expressed as a representative fraction. The representative fraction (RF) is given by:

$$RF = \frac{\textit{photo distance (metres)}}{\textit{ground distance (metres)}}$$

Both photo distance and ground distance are measured in the same units so that the representative fraction is a unitless quantity. For example, suppose that the distance between two points in the photograph is 5 mm and that the corresponding ground distance is 100 m. Then,

$$RF = \frac{5 \times 10^{-3}\text{m}}{100\text{m}} = \frac{1}{20{,}000}$$

It is common to express an RF as a fraction whose numerator is one so that the result can be written as 1:20,000. Table 2 relates photo and ground measurements for a number of common scales and film formats.

Table 2:

Comparison of scales to ground and area covered on a 70 mm^2 or 23 cm^2 photograph.

	Photo distance	Ground distance	Area covered 70 mm^2	23 cm^2
1: 1,000,000	1 mm	1,000 m	4,900 km^2	52,900 km^2
1: 500,000	1 mm	500 m	1,225 km^2	13,225 km^2
1: 100,000	1 mm	100 m	49 km^2	529 km^2
1: 50,000	1 mm	50 m	12.2 km^2	132.2 km^2
1: 20,000	1 mm	20 m	2.0 km^2	21.2 km^2
1: 10,000	1 mm	10 m	0.49 km^2	5.3 km^2
1: 5,000	1 mm	5 m	0.12 km^2	1.3 km^2
1: 1,000	1 mm	1 m	0.0049 km^2	0.05 km^2

The representative fraction (RF) is also given by:

$$RF = \frac{\text{focal lenght of lens (metres)}}{\text{height of camera above ground (metres)}}$$

For example, if a lens of focal length 153 mm is used at a flying height of 3060 m above mean sea-level, then:

$$RF = \frac{153 \times 10^{-3}m}{3{,}060m} = \frac{1}{20{,}000} = 1{:}20{,}000$$

Two observations are important. First, scale varies everywhere in an aerial photograph as a consequence of the fact that flying height above the ground varies everywhere in an aerial photograph. It is common to establish a fixed ground datum (e.g. mean sea level) to determine scale. At best, however, this represents an average or nominal scale. Actual scale varies with local topography.

Suppose, in the previous example, that the ground elevation of points in the photograph varies from mean sea-level to 306 m above mean sea-level. Then, scale varies from 1:20,000 at mean sea-level to:

$$RF = \frac{153 \times 10^{-3}m}{3{,}060m - 396m} = \frac{1}{18{,}000} = 1{:}18{,}000$$

at 306 m above mean sea-level. Second, a given nominal scale can be obtained with different choices of lens and flying height, provided the ratio of focal length to flying height is held constant. The choice of focal length and flying height, rather than nominal scale, often determines the suitability of the photographs for use in stereoscopic viewing.

The forester must know the appropriate scales to work with for a specific management job. Table 3 shows the relationship between some selected scales and corresponding management planning activities.

Table 3: Relation between scales and management activities.

Scale	Categorical detail	Resource activity
1: 1,000,000	Forest Regions	Provincial Planning
1: 250,000	Forest Sections	Regional Planning
1: 50,000	Forest Associations	Extensive Management
1: 20,000	Forest Types	Stand Management
1: 2,000	Individual Tree and Branch Detail	Tree Selection, Tree Management

Vertical exaggeration

When viewed stereoscopically, aerial photographs show varying degrees of vertical exaggeration. For a given scale, the longer the focal length of the lens used (equivalently, the higher the flying height above the ground), the less will be the vertical exaggeration. That is, the stereoscopic image can appear flattened relative to its true relief. Conversely, the shorter the focal length of the lens used (equivalently, the lower the flying height above the ground) the greater will be the vertical exaggeration. That is, the stereoscopic image can appear accentuated from its true relief. Vertical exaggeration is desirable for reliable height measurements and for accurate differentiation of tree stands and fine topographic detail. Aerial photographs can, however, have too much vertical exaggeration which can make stereo viewing difficult or obscure essential detail.

The range of focal lengths available depends upon the camera system used. The range of flying heights available depends upon the type of aircraft used. The following provides some general guidelines:

1. In mountainous terrain, a short focal length lens (less than or equal to 153 mm) causes excessive parallax difference in the photographs which makes stereo viewing difficult.
2. A short focal length lens causes increased displacement due to relief which may render the photographs useless for certain applications. For example, even in areas with modest crown closure, increased relief displacement may cause the ground beneath the trees to be totally obscured, making height determination impossible.
3. Long focal lengths (306 mm or greater) are best for photographs used for mapping (scales about 1:20,000) in rugged terrain.
4. Shorter focal lengths are suitable for 70 mm large scale (1:200 - 1:1000) photographs since the reduced photo size and photo base length act to decrease the parallax difference corresponding to a given change in elevation.

Number of photographs needed

The number of air photos can be calculated once the details of the photo mission are known. A sample calculation is given below corresponding to the following specifications:

1. Nominal scale 1:20,000.
2. Size of photographs 23 × 23 cm.
3. Overlap along line of flight (endlap) 60%.
4. Overlap along adjacent lines of flight (sidelap) 30%.
5. Length of area along lines of 25 km.
6. Width of area across lines of flight 20 km.
7. At least 25% of the width of a photograph shall extend beyond each side boundary of the area.

First, calculate the number of flight lines as follows:

1. The width, in units of ground distance, corresponding to each flight line is given by:

$$\frac{\text{width of photograph}}{\text{RF}} = 20{,}000 \times 0.00023 \text{ km} = 4.6 \text{ km}$$

2. With sidelap of 30%, the net new area covered by each successive flight line is given by: 4.6 km × (1.0 – 0.3) = 3.22 km. Therefore, each line of flight should be spaced 3.22 km apart.

3. With 25% of the width of a photograph to extend beyond each side boundary, the total width of area photographed is given by: width of area (km) + 2 × 0.25 × width of one flight line (km) = 20 km + 0.5 × 4.6 km = 22.3 km

4. Total number of flight lines required is given by:

$$\frac{\text{width of area covered (km)}}{\text{net width of single photo (km)}} = \frac{22.3\text{ km}}{3.22\text{ km}} = 7$$

Flight lines are spaced symmetrically about the centre line of the area.

Second, calculate the number of photographs per flight line as follows:

1. With endlap of 60%, the net new area covered by each successive photograph along the flight line is given by: 4.6 km × (1.0 – 0.6) = 1.84 km

2. Total number of photographs per flight line is given by:

$$\frac{\text{length of area covered (km)}}{\text{net length of single photo (km)}} = \frac{25\text{ km}}{1.84\text{ km}} = 14$$

A standard practice is to add two photographs at the end of each flight line as a safety measure. Thus, 18 photographs are required per line of flight. With 7 flight lines, the total number of photographs needed is 18 × 7 = 126.

Sources of air photographs

To order aerial photographs, it is necessary to specify both the roll and frame numbers desired. For example, A 30339:113 identifies frame 113 on roll A 30339. Two overlapping photographs are required to produce a stereo pair, (e.g. A 30339:112-113). For synoptic coverage, without stereo overlap, it is only necessary to order every second frame.

Sources of Landsat satellite images

Since 1972, Landsat satellite images have been available on a continuous basis for most places in Canada. Each Landsat satellite passes a given location in Canada once every 18 days. Cloud conditions and occasional equipment problems reduce the number of useful scenes available. To order a Landsat satellite image, it is necessary to specify both the path and row number of the image desired.

Handling and storage of aerial photographs

Photos should be stored under constant conditions. They should be protected from extremes of temperature and humidity which can cause shrinkage and expansion of the paper. A special filing cabinet which keeps photos pressed tightly together is advantageous so that curling and cracking can be minimized.

When used in the field, photos should be provided with a stiff, transparent celluloid envelope or wrapped in a plastic sheet and should not be left exposed to direct sunlight.

Principles of Stereoscopy

Using a single eye, the shape, size, arrangement and shadow patterns of familiar objects can be associated with depth or distance so that hills and valleys can be recognized, though not seen stereoscopically. True depth perception requires the use of both eyes.

The perception of depth results when an object is viewed from two viewing directions so that two lines of sight converge on the object viewed. The angle of convergence is large for close objects and small for distant objects. Normal human vision fuses object images from two viewing directions (both eyes) to create a three-dimensional image. The art of viewing objects or images in three-dimensions is called stereoscopy.

In aerial photography, each point on the ground is photographed from two different positions. In each case the camera records a view of an object from a different direction. When a person views these two consecutive photos, with each eye looking at a different photo, the two photo objects are fused into one three-dimensional model of the area photographed. The effect is of one eye looking down from the first camera position and the other eye looking down from the second position. Different ground elevations create different angles of convergence when the two images are fused, causing vertical positions in the three-dimensional model to correspond to the actual topography. Thus, the viewer is able to perceive depth from the photos.

Preparation of aerial photographs for stereoscopic viewing

To prepare aerial photographs for stereoscopic viewing, it is necessary to mark the location of the principal point, conjugate principal points and line-of-flight (l-o-f) on each photograph. Points are marked with a circled pin-prick. It is customary to use red ink in a drop-centre pen set at a radius of 5 mm. Lines are scribed using a pin or other sharp edge to penetrate the emulsion layer of the photograph. The scribed line can be filled with a soft red pencil and the excess colour removed with a pencil eraser.

The principal point is the optical centre of the photograph. In a vertical aerial photograph, the principal point corresponds to the point on the ground exactly beneath the aircraft at the precise time of exposure. The principal point is determined by the point of intersection of lines joining the fiducial marks on each side (or corner) of the photo.

The conjugate principal points are locations on one photo of the principal focus points from adjoining photos along the same flight line. Conjugate principal points are located and pin-pricked while viewing the corresponding photos stereoscopically.

The l-o-f marks the true ground track of the aircraft along the flight line. The l-o-f is located by joining the principal point to each conjugate principal point. Because of crosswind, the principal point and two conjugate principal points do not necessarily lie on a single straight line. For the same reason, the l-o-f rarely passes through the side fiducial marks. Thus, the only reliable way to determine the l-o-f is to correctly locate the principal and conjugate principal points.

The l-o-f is oriented so that it is parallel to the line joining the viewer's eyes. The photos are placed in the correct order. If the photo order is reversed, a pseudoscopic image will result, with high elevations appearing as depressions. The viewer should also place the two photos so that the shadows fall toward him. Otherwise, the image may again be a pseudoscopic image.

The stereoscope is set above the photos parallel to the l-o-f. The photos are drawn apart and adjusted until a three-dimensional image is viewed through the stereoscope. The distance between the photos depends on the viewer's eyes and type of stereoscope used. At the correct separation both photos are taped down with the l-o-f in alignment. This step is necessary because prolonged viewing requires precise photo alignment to obtain a correct stereoscopic image and to avoid eye strain. The viewer should sit in a comfortable position with good direct and indirect lighting.

Stereoscope use

The two most common types of instruments used to produce a three dimensional effect are: the lens stereoscope and the reflecting (mirror) stereoscope.

The lens stereoscope modifies the normal eye convergence with magnifying lenses which lengthen the focal length of the eyes. Thus the line of sight of the eyes becomes parallel, or nearly so. For best depth perception and efficient viewing without eye strain, the lens stereoscope should be moved directly over the object being studied so that the viewer can look vertically onto the image through the magnifying lens.

The reflecting stereoscope uses two mirrors to reflect the lines of sight of each eye onto the photograph. With the mirror stereoscope the total area of overlap can be viewed stereoscopically without shifting the instrument as is necessary with the lens stereoscope.

Measuring displacement due to relief

Displacement due to relief refers to the change in photo position of a given ground location as a function of elevation. For example, a tree top will be recorded on the photograph at a point different from where the base of the tree vertically below it is recorded (see Figure 3). Displacement due to relief is always radial from the

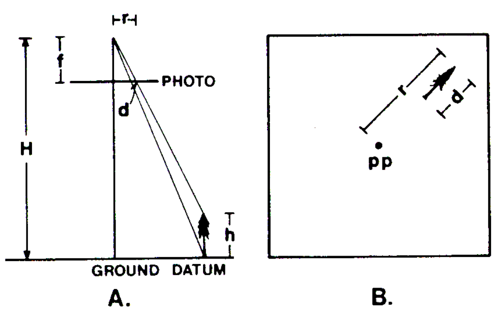


Figure 3:
Displacement due to relief in a single photograph. A) as the photograph is taken, B) as the photograph appears.

Relief displacement is determined by the formula:

$$h = \frac{dH}{r}$$

where: d = displacement due to relief from the top to the bottom of a vertical object, measured in the photograph.

r = distance from the top of the displaced object to the principal point, measured in the photograph.

h = height of object measured between the displaced point (top of object) and the reference point (bottom of object).

H = flying height of aircraft above the reference point (bottom of object).

principal point in a vertical aerial photograph. Points above the elevation of the principal point will be displaced radially outward, whereas points below the elevation of the principal point will be displaced radially inward.

From this formula it can be seen that the higher the airplane flies when taking photos the less will be the displacement due to relief. Also apparent from the formula is the fact that displacement due to relief is proportional to distance from the principal point. The farther away from the centre of the photograph the greater will be the displacement. If the displacement of identifiable vertical objects such as buildings, or trees can be measured, then the height of these objects can be calculated using the above formula.

Measuring parallax difference

The height of an object can be determined accurately with stereoscopic viewing. Measurement of the combined effects of displacement due to relief in the two overlapping photographs is used to determine object height and terrain elevation.

Parallax is the term used to denote the displacement of one object in relation to another caused by a shift in the position of observation. More formally, the absolute stereoscopic parallax (x-parallax) P at a point is defined to be the algebraic difference, measured parallel to the line of flight, of the distances of the two images from their respective principal points.

Referring to Figure 4, the absolute stereoscopic parallax at the top of the tree is given by:

$$P_{TOP} = a' - (-b') = a' + b'$$

The absolute stereoscopic parallax at the base of the tree is given by:

$$P_{BASE} = a - (-b) = a + b$$

(Note that distances measured to the right of the principal point are considered to be positive while distances measured to the left of the principal point are considered to be negative.)

All techniques used to measure object height and terrain elevation from stereoscopic models involve the determination of the amount of parallax. Parallax can be measured directly, as indicated above, but it is generally more convenient to measure the parallax difference, dP, between two points of interest.

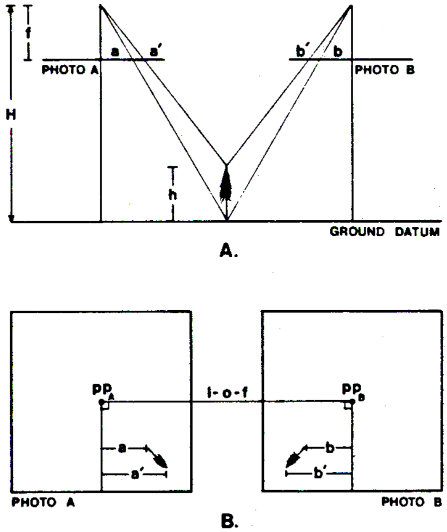


Figure 4:
Displacement in stereoscopic pairs of photographs. A) as the photographs are taken, B) as the photos appear. Similar triangles are used to derive.

The basic parallax formula is:

$$h = \frac{HdP}{P + dP}$$

where:
- h = height of object
- H = flying height of the aircraft above the base of the object
- P = absolute steroscopic parallax at the base of the object
- dP = parallax difference between the top of the object and the base of the object.

This formula is exact when the flying height H above the base of the object is the same for both photographs and when both photographs are truly vertical. It would seem, however, that it is still necessary to determine P, the absolute stereo-scopic parallax at the base of the object. It can be shown that if both principal points have the same elevation and if the base of the object is at this elevation then the required P is equal to the average photo base length 8. This is the average distance between principal and conjugate principal points in the two photographs. The average photo

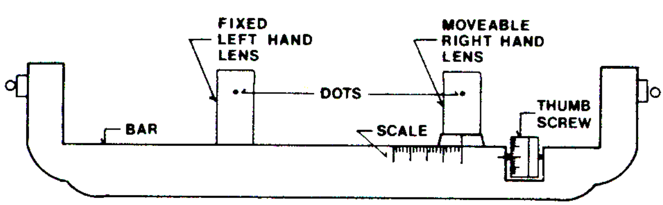


Figure 5: Height-finder.

base length 8 is often used to approximate p in applying the parallax formula.

Parallax difference, dP, is readily determined with a floating mark device called a stereometer or height finder (see Figure 5).

The height finder is used with a lens type stereoscope and consists of a bar which can be attached to the stereoscope. On the left is a permanently fixed piece of transparent plastic positioned in the centre of the field of view of the left lens. A small dot is marked on the plastic. On the right is a similar piece of plastic, with corresponding small dot, positioned in the field of view of the right lens. The right piece is moveable in a direction parallel to the bar (i.e. parallel to the line of flight in the photographs). A thumb screw calibrated in units of 0.01 mm is used to move the dot back and forth.

When viewed stereoscopically, the two dots can be fused into a single dot. Adjustments to the thumb screw cause the fused dot to appear to move up or down. Measurement of dP is made as follows. First, the thumb screw is adjusted so that the dots appear to be at the same elevation as the top of the object of interest. A reading is taken off the scale. Second, the thumb screw is adjusted so that the dots appear to be at the same elevation as the base of the object of interest. A second reading is taken off the scale. The difference between the two readings is the required dP. This value is used in the parallax formula to determine object height h.

Use of aerial photographs in mapping

Modern planimetric and topographic mapping is based largely upon aerial photographs. Good maps and controls are available for many areas and from several government sources. There will, however, occasionally be a need for foresters to prepare local planimetric maps for special purposes. Planimetric mapping can be done using the technique of radial line triangulation.

Radial line triangulation

Radial line triangulation takes advantage of the fact that displacement due to relief in a vertical aerial photograph is always radial from the principal point. That is, vertical aerial photographs provide a precise record of angles, provided those angles are measured from the principal point and with respect to the line of flight (Figure 6). A point X has been located stereoscopically in both photographs. The true ground position of X must subtend angles a and b as shown. If the base map location of principal points PPA and PPB is known, then the corresponding triangle is fixed and its third vertex determines the map position of X.

The following points outline a simple graphical method to prepare maps from vertical aerial photographs using radial line triangulation.

1. All photographs are prepared for stereoscopic viewing. That is, principal points, conjugate principal points and lines of flight are located and marked.
2. Ground control points (GCPs) are points whose map position is known and whose images can be clearly identified in the photographs. GCPs are located and marked in all photographs in which they appear. GCPs determine the scale and orientation of the planimetric map. A minimum recommendation is to have GCPs at each comer of the area to be mapped. For manual techniques, it is useful to have at least one pair of photographs which includes two (or more) GCPs in the area of stereo overlap.

3. Photo control points (PCPs) are points chosen for their location in the photographs. PCPs tie together photographs along a flight line and between flight lines. PCPs are chosen opposite the principal point on each photograph and approximately the average photo base length B away from the line of flight. Each photograph will have six PCPs and a given PCP can appear in six different photographs. Suitable PCPs are located and marked in each photograph.
4. All angles are transferred to a transparent medium such as mylar. One mylar sheet is required for each photograph. The mylar sheet is placed on top of the photograph. The principal point is marked and the line of flight is drawn. Radial lines are drawn from the principal point through each GCP and PCP which appears in the photograph (it is convenient to use different coloured inks for the line of flight, lines through GCPs and lines through PCPs).
5. The location of all principal points is transferred to the base map. Begin with the mylar sheets corresponding to the two adjacent photographs containing the most number of GCPs in the region of stereo overlap. The mylar sheets are superimposed so that the lines of flight coincide. The sheets can be moved closer or further apart, provided the lines of flight remain coincident. By adjusting the position, orientation and spacing of the mylar sheets on the base map, a configuration will be found such that the radial lines through the GCPs intersect precisely at the corresponding map position. When this is done the two mylar sheets can be taped in place. Additional mylar sheets, both along the same line of flight and from adjacent lines of flight are added (a light table will become useful). Each new sheet is positioned so that the required lines of flight are coincident and the required radial lines through PCPs and GCPs intersect at the determined map position. When all mylar sheets have been positioned and taped in place, the location of each principal point is transferred to the basemap (a pin can be used to prick through the mylar and mark the base map).
6. The collection of mylar sheets can be disassembled. The planimetric map position of any point in the area of coverage can now be determined, as illustrated in Figure 6. Two photographs are selected which include the desired point in their area of stereo overlap. The corresponding mylar sheets are superimposed and the required radial lines are drawn. The mylar sheets are then re-assembled on the basemap using the known position of the two principal points to determine the map position of the desired point.

Distance measurements

Simple instruments for measuring distances in aerial photographs include: engineer's scale, microrule and glass scale. Short distances can be measured accurately with instruments such as a zoom microscope. This device can magnify images from 10x to 30x with a built in scale superimposed in the field of view.

Area measurements

Planimeters yield accurate measurements of area when used carefully but are relatively slow. By tracing a closed boundary in a clockwise direction, units of area are counted. Area in the photograph can be converted to hectares on the ground using the nominal scale (see Table 2).

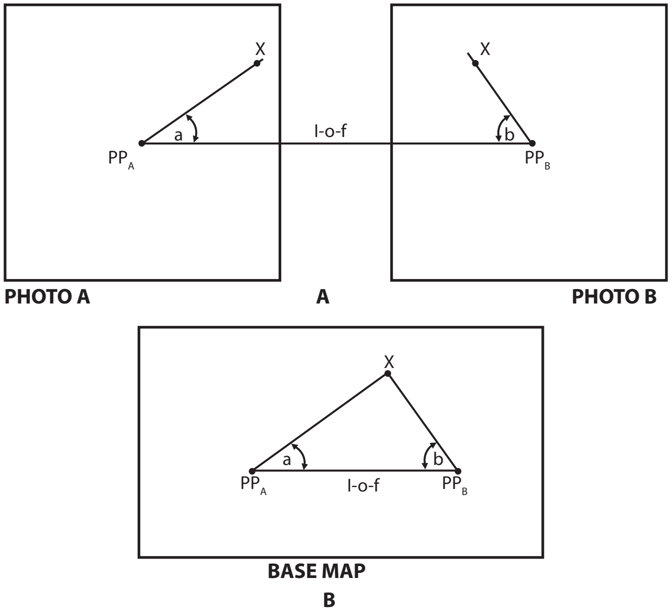


Figure 6:
Radial line triangulation. A) angles a and b determined from radial lines through point X. B) true ground position of X transferred to basemap by forming triangle with base joining principal points PP_A and PP_B and interior angles a and b.

Another way to determine area in the photograph is to use a dot grid. Dot grids consist of a regular distribution of dots at a known density (dots/cm) printed as a transparent overlay. Each dot represents a certain area. Area is estimated by superimposing the grid on the photograph and counting the number of dots falling inside the designated region.

Height measurements

Simple height measurements based on parallax differences are made using a lens type stereoscope and height finder as discussed above. Parallax difference can also be measured with a parallax wedge which consists of two almost parallel lines printed as a transparent overlay. The spacing between lines varies but is calibrated on the wedge, typically in units of 0.05 mm. As the observer looks through the stereoscope with the parallax wedge superimposed, the two lines are fused into a single line sloping in depth. The first reading is obtained by making a subjective judgement as to where the sloping line crosses the plane of the top of the object, and the second reading where the sloping line crosses the plane of the base of the object. The difference between these two readings is the required parallax difference (dP). It takes experience to use a parallax wedge, and many prefer to use a height finder.

Terrain Analysis or Landform Interpretation

The material in this section is discussed in greater detail in Keser (1976).

Photo interpretation features

A landform is defined as a certain arrangement and configuration of surficial materials to produce a characteristic land feature. Throughout the world there are about 35 common landforms. Topography, tone, drainage pattern, gully erosion, vegetation or land use and boundary characteristics are the photo interpretation features used to interpret landforms.

Topography

This feature gives an indication of how the material got to its present location, and/or the resistance of the material to erosion:

- flat topography is usually formed by the deposition of materials in still water;
- knob and kettle topography usually results from the deposition of englacial material through melting glacial ice;
- hilly topography indicates bedrock control.

The first item to look at on an air photo is the topography.

Photo tone of landform

This feature gives an impression of soil moisture:

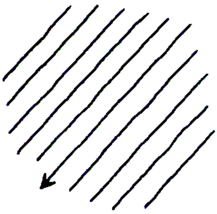
- A light tone indicates dry soil which is usually coarse textured.
- A medium tone indicates a moist soil.
- A dull, drab tone indicates a wet soil which is usually fine textured (note the hot dry weather of the BC interior can air-dry the silty and clay soils, thus making them highly reflective. Such air-dry soils can appear very light to whitish on photographs).
- A uniform tone indicates a uniform soil condition.
- A mottled tone (e.g. light and dark) indicates a variable soil condition.

Drainage patterns

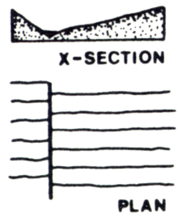
Drainage patterns give an indication of parent material, and/or bedrock control. Drainage patterns do not necessarily have water in them. Some common drainage patterns are described below:

dendritic drainage patterns indicate fine textured parent materials such as till and lacustrine silts or clays

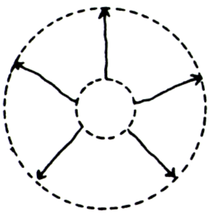
deranged drainage patterns, seen in knob and kettlehole topography, with no integrated pattern indicate dumped glacial till



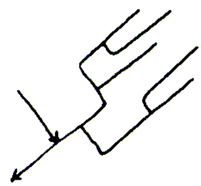
parallel drainage patterns, usually seen on medium to large-scale photographs, indicate gently sloping topography, usually because of bedrock control



trellis patterns, with short parallel and long parallel patterns joining in a central river, indicate tilted, interbedded, sedimentary bedrock



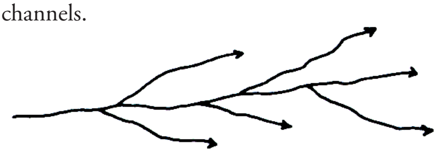
radial patterns are usually seen on cone-like hills such as volcanoes



angular or ***rectangular*** patterns indicate flat lying, jointed, sedimentary bedrock

Specialized drainage patterns

a. *Distributary patterns* are commonly seen on alluvial fans. Distributary patterns are reverse dendritic patterns, the water starts in one channel and breaks into many smaller channels.



b. *Current scars* are seen as darkened, micro-depressions crossing an outwash gravel deposit.

c. *Phantom drainage patterns* indicate an internal drainage. Where the water penetrates the soil the area is darker toned, and contrasts with lighter, drier surrounding areas. If the boundary between light and dark is cloudy, the landform is probably a till plain. If there is a very sharp boundary between the light and dark areas, the landform is probably a transition lakebed or a stratified deposit with commonly coarser textured soils overlying finer textured soils.

d. *Artificial drainage patterns* are common on large, topographically flat, fine textured, lacustrine (marine) deposits. The artificial patterns include ditches, dead furrows, and buried tile drains.

i. Ditches are seen as straight water courses, parallel or close to roads and field edges; material mounded on either side may be a different tone from surrounding soils.

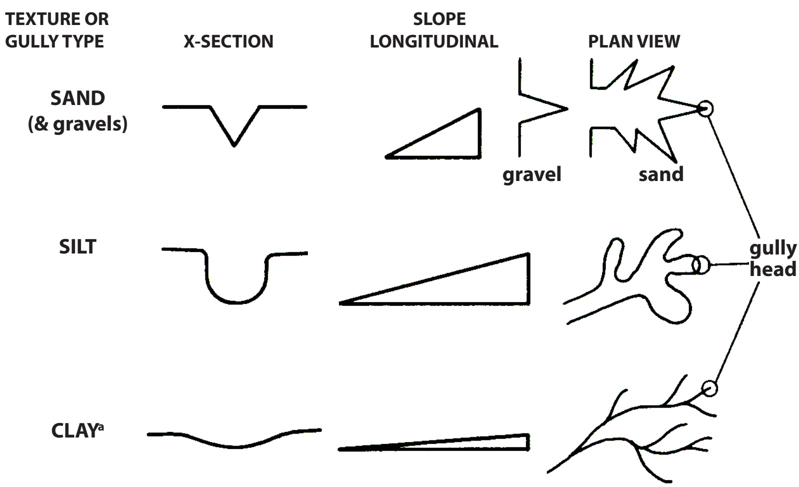
ii. Dead furrows are created in fields by a cultivation pattern, and are seen as dark lines, parallel to each other crossing a field. They do not reach to the edge of the field but stop short by a metre or so.

iii. Buried tile drains usually end in a ditch. They are seen as dark or light lines crossing a field, and are widely separated. There may only be a single tile drain in one field.

On air photos drainage patterns will start on one landform and flow across another landform. The drainage patterns change according to the landform.

Gully erosion

Gully erosion analysis gives another clue to soil texture. To analyse gully features look at the head of the gully, the place where water would start to flow. Gully patterns are best described in terms of the peaks of the soil texture triangle, i.e. sand, silt, and clay.



Vegetation or land use

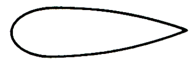
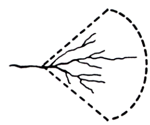
The vegetation or land use on a particular landform is in part dictated by the first four characteristics, however the vegetation or land use does provide an additional clue to the terrain type.

If the vegetation is	*The landform is*
sparse (soil shows through)	dry, suspect gravel
evenly distributed, dense	moist, suspect tills
shrubby, uneven height	wet, suspect fine textured soils (silts-clays), variable pattern

If the landuse is	*The landform(s) are*
agricultural	lakebed, till plain
forested	ground moraine, till plain
mixed	variable

Boundary characteristic

This is the outline of the landform as seen on an air photo. Some landforms are small enough that they are visible on one air photo pair. Other landforms may be so large that an air photo covers only a portion of the landform. Some of the common landforms with their air photo outlines are listed below.

LANDFORM	**OUTLINE**	
DRUMLIN	bullet - shape	
ESKER	snake - like	
ALLUVIAL FAN	fan - like	
TERRACE	stepped	

Till deposits

Till is glacial drift material. Transported and deposited by glaciers, till is fragmented, and it ranges in size from fine clay particles to large pieces of rock. Glacial till is found in landforms such as ground moraines, till plains and drumlins (Table 4).

Table 4: Common till landforms.

Photo Interp. Feature	**Ground Moraine**	**Till Plain**	**Drumlin**
Topography	knob and kettle	smooth sag and well	low hill
Tone	mottled	mottled	light
Drainage pattern	deranged	phantom internal	none
Gully erosion	clay	clay	none
Vegetation landuse	rocky small field mixed vegetation	large fields extensive tracts of forest	Forested
Boundary	not applicable	not applicable	bullet shape
Remark	• difficult to work because of large rocks, water filled kettle holes, the poor drainage decreases potential productivity	• easy to work • few rocks • forms a good, productive site	• may be found with many drumlins or on a drumlinized till plain • productive site

Till is also found pasted on bedrock, and it may be ablation till – with easy root penetration and forming a productive parent material, or basal till which is hard, and compact. Water and roots do not penetrate easily. Bedrock-controlled till is called "till/rock" since the underlying bedrock patterns are seen on the air photos. Because of the bedrock close to the surface, till/rock will pose difficult forest management construction problems.

Gravel deposits

Gravel deposits are important to forest road construction and repair. In British Columbia, gravel deposits were formed during the melting of glaciers when the glacial meltwaters ground and sorted the glacial till and deposited them in stratified deposits (Figure 7). The materials range from sands, through rounded cobbles to boulders. The fine particles such as silts and clays have usually been washed away. Gravels are found in kames, eskers and outwash landforms. Although there are many varieties of outwash deposits that are identifiable on air photographs, they all are important gravel sources (Table 5).

Table 5: Common gravel landforms.

Photo Interp. Feature	Kame	Esker	Outwash
Topography	small conical	long, low winding ridge	flat, may have pits
Tone	light	light	light with dark current scars
Drainage pattern	none	none	none
Gully erosion	none	none	sand-gravel
Vegetation	sparse veg.	sparse veg.	sparse veg.
Landuse	gravel source	gravel source	gravel source
Boundary	circular	snake-like	not applicable
Remarks	Kames and eskers are often found in complexes. There may be small lakes near the eskers.		May be seen as terraces, deltas. Outwash terraces in mountain valleys are also called Valley Train deposits.

Photo Interpretation for Tree Species Identification

Identification of tree species on aerial photographs is a photo interpretation art which can be learned by any person with good stereo acuity. To interpret tree species, five tree characteristics are stereoscopically examined and they are as follows:

1. Crown boundary (outline).
2. Crown topography.
3. Crown tone and hue.

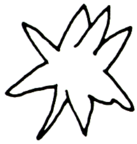
4. Branching habit.
5. Foliage density.

Large scale-photos (greater than 1:5000) are required for positive interpretation of tree species. As the scales become smaller (i.e. 1:10,000; 1:15,000) details of the tree crown merge, and the photo interpreter is looking at tree stands, and not individual trees. Identification of individual trees on small scale photographs is more by luck and *a priori* association than interpretation. The techniques presented here are designed for the large-scale (1:2000) aerial photographs, and can be applied to black and white, colour or colour-infrared photographs. After brief explanations of the photo interpretation characteristics, a key to photo interpretation of some BC tree species is presented (Table 6).

Table 6:
Photo interpretation key to some BC tree species seen on large-scale (± 1:2000) air photographs.

1a	Foliage Tufted	**2**
2a	Large tufts – crown globose, tone light	**PONDEROSA PINE**
2b	Small tufts – crown small, tone medium	**LODGEPOLE PINE**
1b	Foliage Not Tufted	**3**
3a	Crown conical and concave, branches ascending, straight or forked	**4**
4a	Branches ascending, irregular lengths, branch tips broad-arrow shaped	**DOUGLAS-FIR**
4b	Branches not ascending, even regular lengths	**5**
5a	Branches with fan-shaped tips, forked and usually covered with foliage, leader drooping on young trees	**WESTERN HEMLOCK**
5b	Branches straight or curved, rarely forked foliage pendulous, stem of branch visible	**6**
6a	Branchlets hang limply, leader often drooping	**YELLOW CYPRESS**
6b	Branchlet tips turn upwards, branches appear as wagon wheel spokes	**WESTERN REDCEDAR**
3b	Crown spire-shaped, or columnar, foliage dense	**7**
7a	Crown spire-shaped	**SUBALPINE FIR**
7b	Crown not spire-shaped, usually columnar – foliage dense	**8**
8a	Crown columnar or cigar-shaped, branches with dense foliage appear cigar-shaped	**ENGELMANN or WHITE SPRUCE**
8b	Branches appear layered, branch tip pancake-shaped	**GRAND, SILVER, AMABILIS FIR**

Crown boundary or outline



Star-shaped
Douglas-fir
western white pine

Circular
western hemlock (young)
spruce Abies
pines
Douglas-fir
hardwoods

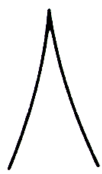
Irregular
hardwoods
open grown
damage of trees

Net patterned
alder

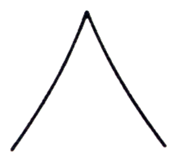
Seen in a vertical view through a stereoscope, tree crowns are either concave or convex.

Concave crowns

Spire-shaped
subalipine fir
balsam fir (*A. balsamea*)
young western hemlock
with a bent leader

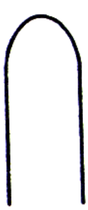


Conical
western redcedar
western hemlock
Douglas-fir



Pyramidal
western redcedar
Douglas-fir
open grown crown

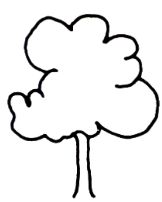
Concave crown (domed)



Sylindrical or cigar-shaped
spruce
old Douglas-fir

Globose

lodgepole pine
ponderosa pine
aspen



Billowy

cottonwood
maple

Tufted

maple

Crown tone or hue

Crown tone is related to the general lightness or darkness of the crown. Hue refers to the colour. Crown tones for a given species are highly variable, and are dependent on the age of the tree and site. Crown tone is useful when one species is being compared to another species.

Light Tones – cedar, pines, young growth trees, stressed trees,

Medium Tones – hemlock, cedar, maturing trees,

Dark Tones – short-needled pines, spruce, some old growth trees.

Branching habit

Branching habit is dependent on branching arrangement, branch direction, and branch form.

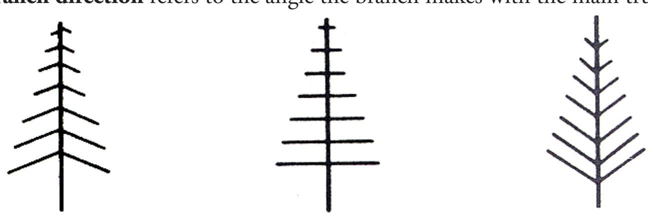
Branch arrangement is the initial pattern of branches along the stem.

X-section plan Opposite
(branches appear
layered, branches are
opposite to each other)
pines
spruce
Abies

X-section Alternate
(branches do not
appear opposite
each other)
hemlock
cedar

Alternate and Spiral
many branches show
hemlock
cedar

Branch direction refers to the angle the branch makes with the main trunk.

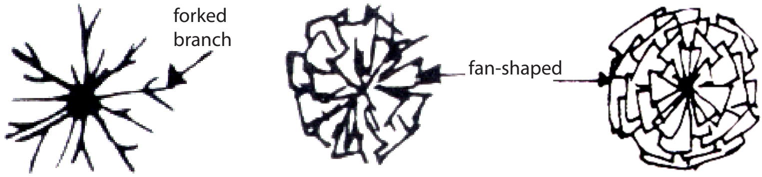


Drooping
Douglas-fir

Horizontal
pines
Abies

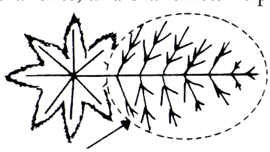
Ascending
spruce
hemlock
cedar

Branch form indicates whether a branch is straight, curved, or forked. Some of these patterns depend on the tree age, for example, the illustration below shows the variation found in western hemlock. Forks of the branches produce fan-shaped branches which become more obvious as the tree matures.

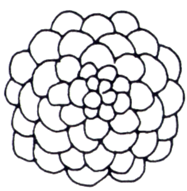


Cedars may occasionally show a forked branch, however, most branches are straight or curved, but they never develop the forked to fan-shaped pattern seen in hemlock.

The ascending branching habit coupled with the tendency to produce opposite branches, and branchlets helps to separate Douglas-fir from other tree species.



Enlarged view of branchlet



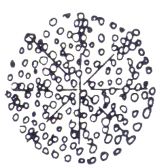
The successive rows of branchlets give Douglas-fir a "broad-arrow" branchtip that appears to point upwards in the stereo view. This pattern is virtually unique to Douglas-fir.

The opposite and almost horizontal branching habit gives some species of the genus *Abies* a layered "pancake" appearance. The pattern is particularly common in amabilis, grand and silver fir. Sometimes the new foliage which has a higher spectral reflectance than older foliage gives a light border to the rounded pancake appearance of the branch ends (the branches are neither broad-arrow pointed or ascending as in Douglas-fir).

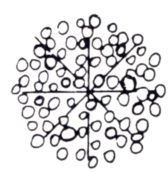
Foliage density and pattern

Foliage density and pattern refers to the arrangement and density of foliage seen on branches.

Clumped in tufts



lodgepole pine (jack pine)



ponderosa pine (red pine)

The tufts of foliage, whether large or small provide easy separation of the two pines.

Pendulous, with the branches visible

The branchlets with foliage hang down. This is a common pattern for the cedars, consequently on air photos the branches are visible and the crown appears thin. **Striated,** seen in stereo view on air photos. The foliage of hemlock covers the entire branch and the branch appears “hairy”. The stem of the branch is not visible. The foliage gives the hemlock branch a width or thickness greater than the stem alone. The pattern is similar to a plan view of an Irish-setter tail.

Cigar-shaped. Spruce, such as white and Engelmann have a cigar-shaped crown. The foliage on the branches also gives a rounded cigar-shaped appearance. The foliage is dense and compact, the branch stems are not seen. Since the branches are also drooping, these features help to distinguish spruce from Douglas-fir.

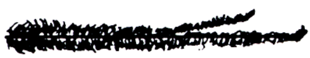


Photo Interpretation of Colour and Colour Infrared Aerial Photographs

The image of an object in an aerial photograph is dependent upon scene radiance, which is the sum of all light reflected back through the camera lens to the film. The most important part of scene radiance is the spectral reflectance of an object. Spectral reflectance is the reflectance of electromagnetic energy in specific amounts in various parts of the spectrum. Green leaves largely absorb light in the red and blue regions of the spectrum (because of chlorophyll a and b absorption), thus the reflectance of red and blue light is very low (±10%). Chlorophyll reflects green light ±20%, thus we see leaves as green. Plants also reflect highly (±60%) in the invisible to the human eye near-infrared region (0.7 to 9.7 micrometers) of the spectrum. A generalized spectral reflectance pattern for green vegetation is given in Figure 8.

Generally, hardwoods are more reflective than conifers but there is a large region of overlap. Factors such as tree age, foliage age, time in the growing season, nutrient status, moisture condition and tree condition, are just some of the causes of variation in the spectral reflectance pattern.

Because of the availability of a wide variety of filters and films, it is possible to take a photograph in any one of the spectral regions. Thus, we could obtain a blue, red, or a near-infrared spectral region photo. Such a series of photos would be called “multispectral” photographs. Colour films are tri-emulsion films, with each of the emulsions sensitive to a particular spectral band. In normal colour film, the yellow, magenta, and cyan dye-forming emulsions are sensitive to blue, green, and red light respectively. In colour-infrared film, the yellow, magenta and cyan dye-forming emulsions are sensitive to green, red and near-infrared light respectively. Thus in both colour films, the dye-forming layers are identical, except that in colour-infrared

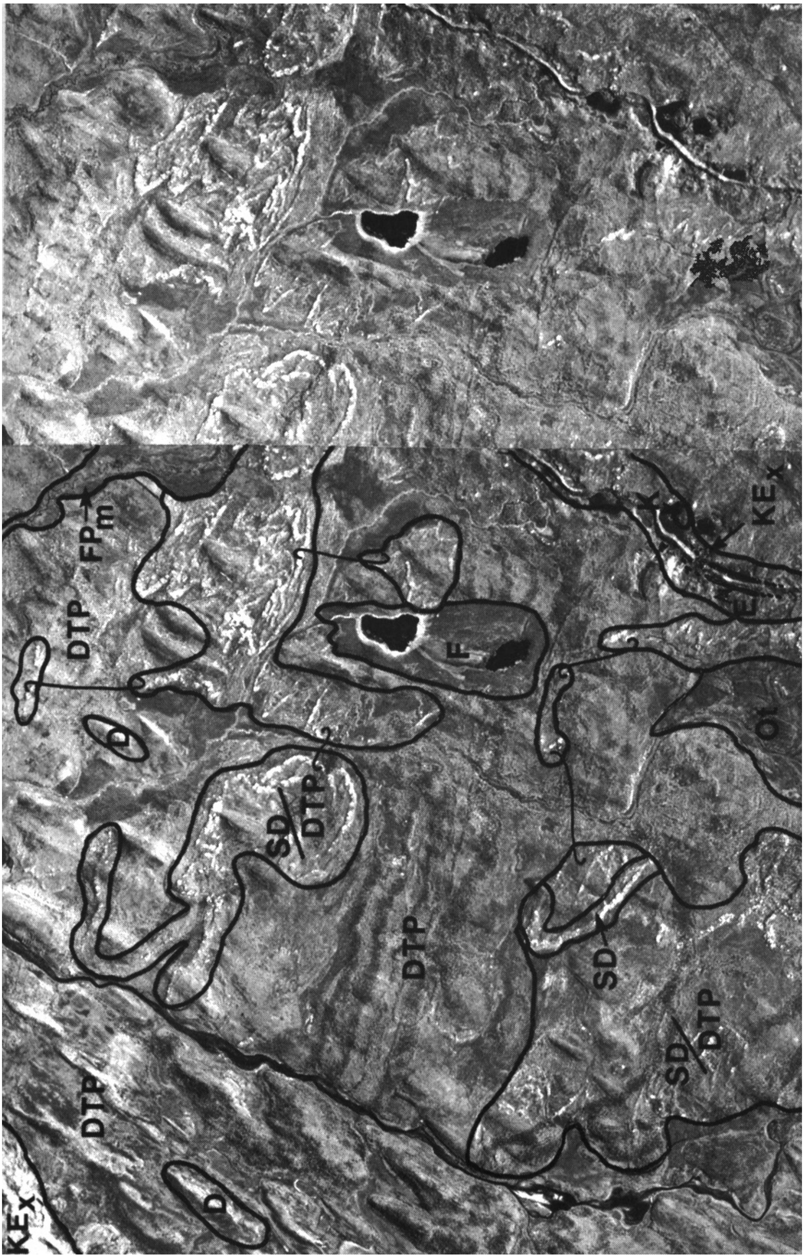


Figure 7:
Landforms: stereoview showing some examples of common landforms; air photo scale is about 1:40,000. Compound legend names represent stratified deposits (i.e. L/ DTP).

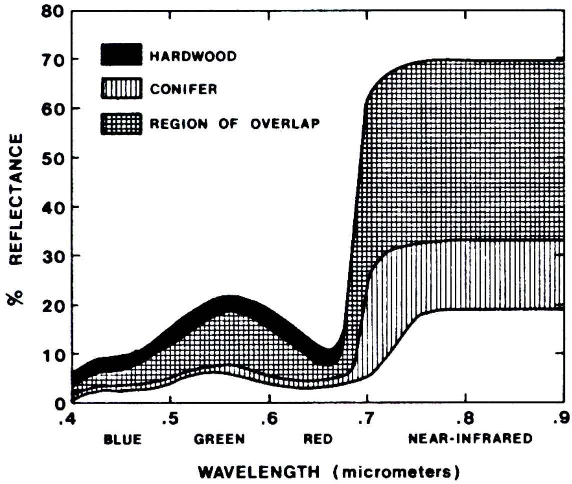


Figure 8:
A generalised spectral reflectance pattern which shows a visual peak reflectance in the green spectral region and an invisible to our eyes spectral peak in the near-infrared spectral region.

film the sensitivities have been shifted up one spectral region. It is emphasized here that normal colour film is sensitive to the same spectral regions as our eyes, and that colour infrared film is sensitive to green, red and the "invisible-to-human-eye" near-infrared region.

An orange, lemon, and lime would prove to be exceedingly difficult to interpret on a black and white photograph, since the uniquely identifying spectral differences have been reduced to grey-tones. With colour films, the spectral differences among objects are maintained and recorded separately by the various dye-forming layers. To illustrate this point for both normal-colour, and colour-infrared film the example of a green leaf, which becomes stressed and dies is used. As a leaf is stressed and dies, its spectral reflectance pattern changes. There are three basic changes which deviate from the normal pattern as seen in Figure 9. First, there is some indication in the

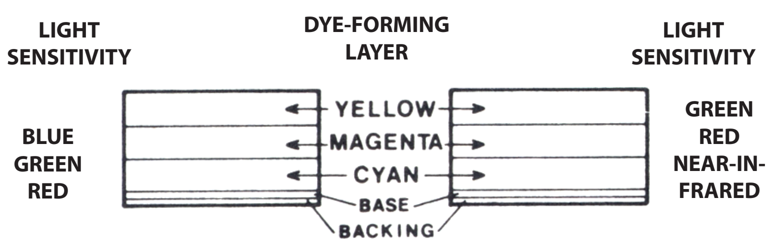


Figure 9:
Schematic representation of the dye-forming layers in normal colour, and colour infrared films. [It is noted here that in the film manufacture, in colour-infrared film, the cyan layer is on the top, with yellow and magenta layers below (Fritz 1967). The patterns above are given in order to facilitate explanation.]

scientific literature that the first change is a change in the near-infrared reflectance pattern. This change is due to changes in cellular inclusion, (crystals, cytoplasm, etc.) and is similar to changes concurrent with the senescence of a leaf as it progresses through the growing season. [The spectral change is not due to structural changes in the structure of the spongy mesophyll or to minor changes in turgor pressure]. The next change is the continued degradation of the cellular inclusions which are exemplified by the breakdown of the chloroplasts. Thus the leaf turns yellow. This is noted as a shift in the green spectral reflectance peak towards the red spectral region. Finally the cells die, moisture is lost, the cells collapse, and the leaf appears the typical dead redbrown colour. At this point the spectral reflectance has decreased in the green, increased in the red, and partially dropped further in the near-infrared. If the leaf is air dry it has a high near-infrared reflectance, and if it has been rained upon and is wet, it has a low near-infrared reflectance. These patterns (1) the normal leaf, (2) the n-IR changed leaf, (3) the yellowed leaf, and (4) the dead redbrown leaf are illustrated in Figures 10A and 11A as changes in spectral reflectance patterns.

The reactions of the dye-forming emulsions are directly related to the spectral reflectance pattern. The amount of dye formed after reversal development is inversely related to the reaction of the dye-forming layer to spectral reflectance. Thus a low level of reaction caused by a low-spectral reflectance pattern will ultimately yield a thick density of dye. Similarly a high level of spectral reflectance in a given spectral region will give a large reaction in the dye-forming layer, and after reversal development, a thin layer of dye is formed. Dyes in positive transparencies are subtractive, and serve to subtract light (Figure 2).

Normal-colour film reaction

If a green leaf is photographed the following happens. Because of the low level of blue and red reflection (Figure 10A) there are low-level reactions in the blue-sensitive yellow dye-forming layer and in the red-sensitive cyan dye-forming layer (Figure 10B). Because of the higher level of green reflectance there is a greater reaction in the green-sensitive magenta dye-forming layer. After reversed development, relatively thick layers of yellow and cyan dyes are formed, as well as a relatively thin layer of magenta dye (Figure 10C). The positive transparency is viewed with transmitted white light. The thick yellow-dye subtracts out blue light, the thick cyan dye subtracts out red light, and the thin magenta dye does little to attenuate the green light. Thus our green leaf is seen as green. In a similar fashion the yellow colour of sick leaves and the dead redbrown colour of dead leaves can be explained. It is important to note that normal colour film does not respond in any way to non-visual (near infrared) changes in spectral reflections.

The chief advantage of normal colour film is the presentation of familiar colours to the non colour-blind interpreter. Dead redbrown tree crowns are easily spotted among many green crowns, slight green and yellow foliage hues are recorded, and their significance for tree condition, site differences, etc., can be assessed. The chief disadvantage is the effect of haze on the photographs. Since the film is sensitive to blue light. where haze scattering of light is a problem, the photographs are also affected. From high altitudes, minor differences in green are easily lost.

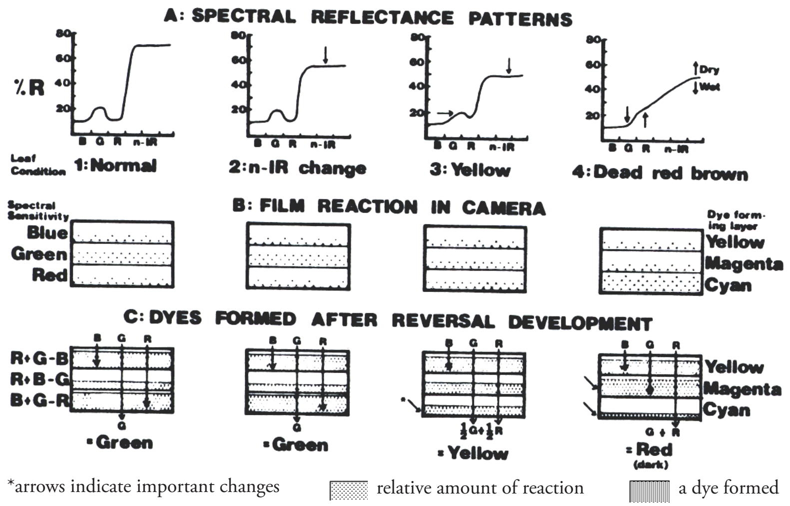
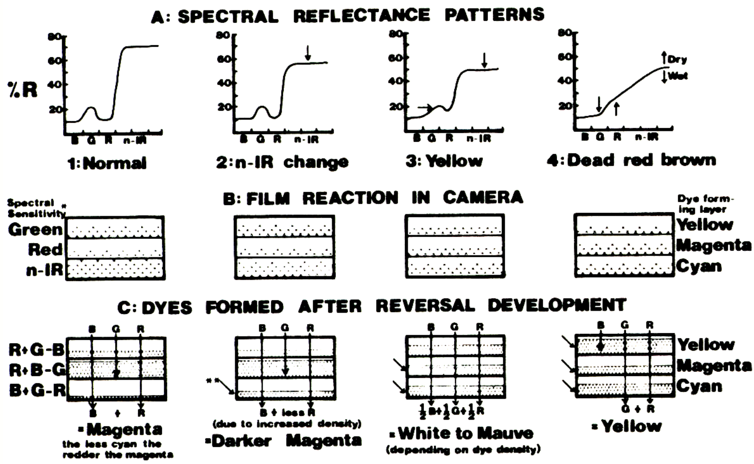


Figure 10:
Response to spectral reflectance changes by the dye-forming layers and development of dyes in *normal colour film*. Colours indicated are seen when the transparencies are viewed with transmitted light.

Colour-infrared film reaction

A Wratten #12 or #15 (minus-blue light) filter is always used with colour-infrared film to eliminate the effects of blue light. Although all dye-forming layers are sensitive to blue light, the use of the minus-blue filter eliminates this problem. Since the dye-forming layers are also sensitive to green and red light, the colour infrared film can be used like a normal colour film. It is not necessary to focus in the near-infrared.

If a normal green leaf is photographed with colour-infrared film, the following happens (Figure 11): Because of the medium, low and high levels (Figure 11A) of spectral reflectance in the green, red and near-infrared respectively, there is a medium level of reaction in the green-sensitive yellow-dye-forming layer, a low level reaction in the red sensitive magenta dye-forming layer, and a high level of reaction in the near-infrared sensitive cyan dye forming layer (Figure 11B). After reversal development there are medium, thick and thin densities respectively of yellow, magenta, and cyan dyes formed (Figure 11C). When viewed with white transmitted light, the medium density of yellow dye subtracts some of the blue light (but not all), the thick density of magenta dye subtracts the green light, and the thin layer of cyan dye does not subtract much of the red light. Thus some blue and red light are transmitted, and the green light is attenuated. Since blue and red combine to give a magenta hue, the visually green leaf is seen as magenta or reddish on colour infrared photos. If there is a decrease in the near-infrared light, such as occurs when a plant becomes stressed, the only result is a thickening on the cyan dye-layer. Consequently the image will appear a darker magenta. Since conifers have a lower near-infrared reflectance than do hardwoods, the conifers will appear a darker magenta than do the hardwoods.



* each of the dye forming layer is sensitive to blue light, but use of a minus-blue (e.g. Wratten 12 filter) prevents unwanted blue exposure of the dye layers.

** arrows indicate important changes.

Figure 11:
Response to spectral reflectance changes by the dye-forming layers and develoment of dyes in colour-infrared film. So-called "false-colours" are seen when the transparencies are viewed with transmitted light.

The secret to interpretation of colour-infrared photographs is knowing how to interpret the false-colours of various objects. The colours are related to the spectral reflectance pattern. The levels of reflectance in the various spectral bands (i.e. green, red, or near-infrared) affect the dye-forming layers. The amount of dye-formed after reversal development is inversely related to the effect of the spectral reflectance in the dye-forming layer. The dyes subtract light, yellow subtracts blue, magenta subtracts green and cyan subtracts red. Thus the stressed-yellow leaf with its reduced near-infrared reflectance will appear mauve, whereas a dead red-brown leaf will appear yellow to a light straw-yellow. Such foliage has a different reflectance pattern from healthy yellow foliage, such as the petal of a yellow tulip flower or the yellow cap of a skunk cabbage flower. Because healthy foliage has a high near-infrared reflectance, as well as high levels of green and red (which is necessary to give a bright yellow), all dye-forming layers will be equally affected, all will be very thin, and when viewed with white light, the yellow tulip will appear white or clear. The dead, straw yellow foliage of a dead ponderosa pine commonly appears whitish on colour-infrared photos. The false colour appearance of some forest subjects is given in Table 7.

The chief advantage of colour infrared film is that it records near-infrared reflectance patterns which cannot be done with normal colour film. Since there are large reflectance differences between the green, red and near-infrared, visually subtle reflectance differences are enhanced and made easier to interpret. Thus

Table 7:
Comparison of normal colour of an object with the false-colour appearance on colour infrared photographs.

Object	Normal colour	Colour-infrared photo appearance
Hardwood foliage	green	magenta to light magenta
Coniferous foliage	dark green	dark magenta
Young conifers	green	magenta
Old conifers	green	light or dark magenta
Chlorotic foliage	yellow	mauve
Autumn hardwood foliage	autumn yellow	light, white or clear
Autumn hardwood foliage	autumn red	bright yellow
Dead, dry foliage	straw yellow to redbrown	whitish to yellow to yellow green
Defoliated branches	grey to brown-black	blue-green, cyan, dark cyan
Defoliated branches, exfoliated bark	whitish	silvery, silvery green
Wet branches, exfoliated bark	dark grey	cyan to dark cyan

spectral contrasts are emphasized. Because a minus-blue filter is used, haze does not affect the film, and since the longer near-infrared wavelengths are used, the film is said to penetrate haze. Thus it is very useful for photography from high altitudes. When used at low altitude, for large photographic scales, subtle differences in near-infrared reflectance patterns, which can be indicative of true condition, are recorded.

Vegetation Damage Interpretation

A stress factor, either biotic or abiotic, affecting vegetation causes strain symptoms to be produced by the tree. Damage is loss, either economic or biologic, due to the stress factor. Stress factors are not directly interpreted from air photographs, but are only inferred from the strain symptoms. The sequences of strain symptoms can often be used to associate the strain symptoms with a given stress factor. In remote sensing and photo interpretation, the interpretation of strain symptoms, their relation to and the identification of stress factors, and the subsequent assessment of loss, have been collectively called vegetation damage.

To interpret vegetation damage on aerial photographs an interpreter must know:

(a) the possible stress factors operative in an area,
(b) the strain symptoms or manifestation of stress produced by the plant,
(c) the effect of the changing strain symptoms on spectral reflectance, and
(d) the effect of spectral reflectance changes on a photographic film.

(a) **Possible stress factors** include all possible causes of vegetation damage in a forest. The vectors range from animal, insects and diseases, to air pollution, fire, weather and site effects. The major problem faced by the interpreter is that any one stress factor can potentially cause a wide variety of strain symptoms, and to adequately interpret the damage, all strain symptoms must be evaluated.

(b) **The strain symptoms** produced by a stress factor are highly variable. The problem is that any one strain symptom can be potentially caused by a wide variety of stress factors. Strain symptoms, or manifestations of damage fall into two basic categories, and are either morphological or physiological in character. Morphological symptoms involve a change in form, whereas physiological symptoms involve a change in function. These basic differences have been used to develop a key to the photo interpretation of forest tree strain symptoms called Damage Types. The Damage Types are a convenient photo interpretation method to classify the myriad of strain symptoms that may be manifested by a stressed tree. It is important to note that a tree may display more than one symptom, for example a dead top (damage type IIA) may be found on a conifer with a thin crown (damage type IIE) which is indicative of premature loss of older foliage, with some of the residual foliage yellowish (IIIA) and some of the other residual foliage dead and red-brown in colour (IIIH). Such a grouping of damage types indicates chronic stress operative over a long period of time (i.e. low levels of air pollution, adverse site conditions, or even a root rot). It is also important to note that varying degrees of symptoms may be seen on a tree. The most common would be the pre-mature loss of older foliage (IIE). Some trees have very little residual current foliage and a large number of branches are evident, or the stressing factor could only be starting and the crown does not show as many bare branches. In such a case the interpreter can add modifying descriptors to the damage, such as $IIE_{(heavy)}$, or $IIE_{(light)}$.

Digital Image Analysis

Digital image

Remote sensing images are representations of parts of the earth surface as seen from space. The images may be analog or digital. Aerial photographs are examples of analog images while satellite images acquired using electronic sensors are examples of digital images. In a most generalized way, a digital image is an array of numbers depicting spatial distribution of a certain field parameters (such as reflectivity of EM radiation, emissivity, temperature or some geophysical or topographical elevation. Digital image consists of discrete picture elements called pixels. A digital image comprises of a two dimensional array of individual picture elements called pixels arranged in columns and rows. Each pixel represents an area on the Earth's surface. A pixel has an intensity value and a location address in the two dimensional image. The address of a pixel is denoted by its row and column coordinates in the two-dimensional image. The intensity value represents the measured physical quantity such as the solar radiance in a given wavelength band reflected from the ground, emitted infrared radiation or backscattered radar intensity. This value is normally the average value for the whole ground area covered by the pixel.

Data format

Satellite imagery basically comes in three formats: BIL – Band Interleaved by Line; BSQ – Band Sequential, BIP – Band Interleaved by Pixel (Table 8). The BIL format is more common than the BIP or BSQ formats.

Image resolutions

Resolution can be defined as "the ability of an imaging system to record fine details in a distinguishable manner". A working knowledge of resolution is essential for understanding both practical and conceptual details of remote sensing. Along with the actual positioning of spectral bands, they are of paramount importance in determining the suitability of remotely sensed data for a given application. The major characteristics of imaging remote sensing instrument operating in the visible and infrared spectral region are described in terms of:

(i) spectral resolution,
(ii) radiometric resolution,
(iii) spatial resolution and
(iv) temporal resolution.

Details for these resolutions are given in Table 9 for Landsat-7 Enhanced Thematic Mapper.

Spectral resolution: refers to the electromagnetic wavelength range of the spectral bands. Different material on the earth surface exhibit different spectral reflectance and emissivities.

Radiometric resolution: refers to the smallest change in intensity level that can be detected by the sensing system. It is commonly expressed as the number of bits (binary digits) needs to store the maximum level. For example Landsat TM data are quantised to 256 levels (equivalent to 8 bits).

Spatial resolution: refers to the size of the smallest object that can be resolved on the ground. In a digital image, the resolution is limited by the pixel size, i.e. the smallest resolvable object cannot be smaller than the pixel size (Figure 12).

Temporal resolution: refers to the frequency with which images of a given geographic location can be acquired. Satellites not only offer the best chances of frequent data coverage but also of regular coverage.

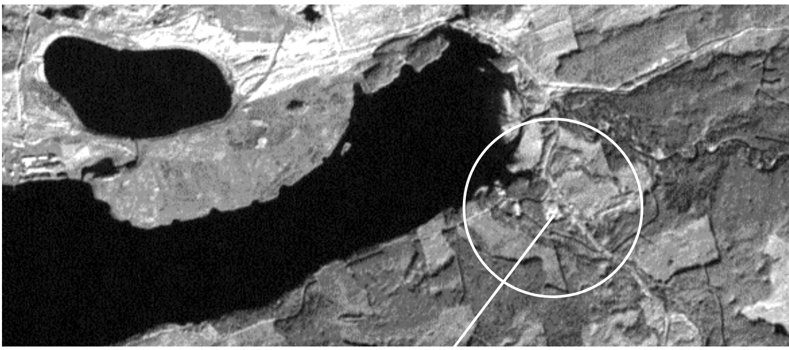
Colour combinations

A number of spectral band combinations have been found to be suitable for the extraction of various resources related information, through visual interpretation methods. The personal preference of the image interpreter also influences the selection of spectral band combinations. For mapping of surface cover types, mapping of water sediment patterns, a normal colour composite is preferred. Band combination 4,3,2 (FCC) is found particularly suitable for discrimination amongst various vegetation types. For many other applications such as mapping of urban features and broad vegetation types the combinations of 4,5,3; 7,4,3; 5,4,3 are preferred. Incorporation of short-wave infrared bands further enhances the vegetation discrimination capability.

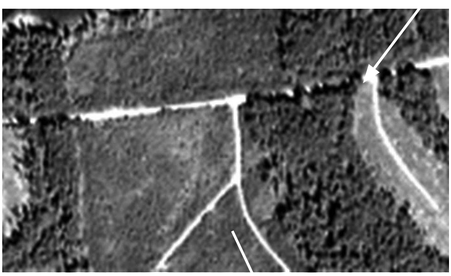
Data merging/fusion

Many applications of multi-spectral remote sensing data are enhanced through fusion of multiple data sets covering the same geographical area. These data sets can be of different spatial resolutions, sensors and acquisition dates. One of the most common data merging application is in combining coarser resolution multi-spectral data with high resolution panchromatic data. This is also called "Pan sharpening".

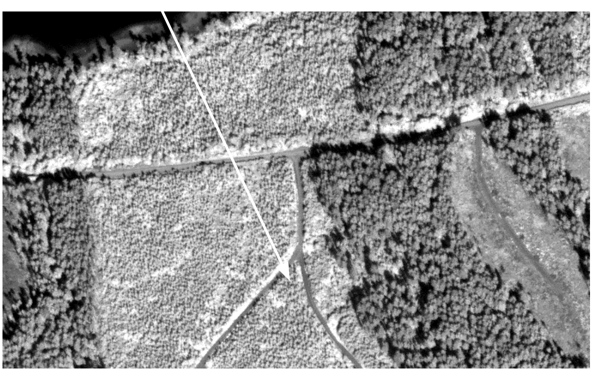
Landsat-7 ETM^{+}
Normal Colour Composite Spatial Resolution: 30 m



Landsat-7 ETM+, Panchromatic, Spatial Resolution: 15 m



IKONOS Multi-spectral Normal Colour Composite Spatial Resolution: 4 m



IKONOS Panchromatic, Spatial Resolution: 1 m

Figure 12: Details seen at different spatial resolutions.

Table 8: Data layout in different image formats.

BIL: Band Interleaved by Line: A 4 band image in the BIL format would look like this (the numbers indicate the band):

1111111111	(10 columns of first row)
2222222222	
3333333333	
4444444444	
1111111111	(10 columns of second row)
2222222222	
3333333333	

BIP: Band Interleaved by Pixel: The BIP format is organised with all bands of the image sequentially defined for each pixel:

1234 1234 1234 1234 ...	(4 cols of 1st row)
1234 1234 1234 1234 ...	(4 cols of 2nd row)

BSQ: Band Sequential
BSQ format separates the individual bands for the complete scene:

1111111111	(first row of band 1)
1111111111	(second row of band 1)
...	
2222222222	(first row of band 2)
2222222222	
...	
3333333333	(first row of band 3)
3333333333	
...	
4444444444	(first row of band 4)
4444444444	

Table 9: Resolution details of Landsat-7 Enhanced Thematic Mapper (ETM[a]).

Spectral bands	Spectral-range (μm)	Spatial (m)	Radio-metric	Temporal (Revisit)
Band 1 (Blue-green)	0.450 – 0.515	30	8 bit	16 days
Band 2 (Green)	0.525 – 0.605	30		
Band 3 (Red)	0.630 – 0.690	30		
Band 4 (Near Infrared)	0.750 – 0.900	30		
Band 5 (Short wave NIR-I)	1.55 – 1.75	30		
Band 6 (Thermal)	10.40 – 12.50	60		
Band 7 (Short wave NIR-II)	2.09 – 2.35	30		
Band 8 (Panchromatic)	0.520 – 0.900	15		

[a.] Note: Landsat-7 satellite was launched on April 15, 1999.

Image classification

Digital image analysis is usually conducted using raster data structures – each image is treated as an array of values. It offers advantages for manipulation of pixel values by image processing system, as it is easy to find and locate pixels and their values. Many image processing and analysis techniques have been developed to aid the interpretation of remote sensing images and to extract as much information as possible from the images. The choice of specific techniques or algorithms to use depends on the goals of each individual project. **Digital Image Classification** is the process of sorting all of the pixels in an image into a finite number of individual classes. Fundamentally, spectral classification forms the basis to map objectively the areas of the image that have similar spectral reflectance/emissivity characteristics. Depending on the type of information required, spectral classes may be associated with identified features in the image (supervised classification) or may be chosen statistically (unsupervised classification).

Unsupervised classification

In an unsupervised classification, the objective is to group multi-band spectral response patterns into clusters that are statistically separable. The basic assumption is that the digital values within given cover types are close to each other in measurement space, whereas data in different classes are comparatively well separated. This system of classification does not utilize training data as the basis of classification. This classifier involves the clustering algorithms that examine the unknown pixels in the image and aggregate them into a number of classes based on the natural groupings or cluster present in the image.

Supervised classification

Supervised classification generally refers to pattern recognition, which is a process to categorize or classify each image pixel into one of the pre-specified classes. It is a two-step process in which:

1. The classes of interest are characterized through analysis of data, which are representative of the class. This step is called training the classifier.
2. All the data are classified by means of numerical rules (decision rules/ classifier) which utilize the class characteristics.

Training the classifier

Ground truth information is used in this step to identify areas which correspond to various classes on the ground, and information about each class is derived from this representative set. These classes are located by fieldwork or from air photographs or map interpretations and their position on the image is found either by visual interpretation or by carrying out geometric correction of the image. Normally training fields are located as blocks of pixels, either rectangular or polygons. From these training sites, statistical properties of the classes are estimated and tested for statistical separability between various training classes.

Classification procedures

During this step, by using various statistical approaches each pixel is categorized into land cover class to which it closely resembles. If the pixel is not similar to the training data, then it is labelled as unknown. Numerical mathematical approaches to the spectral pattern recognition have been classified into various categories.

Minimum distance to mean classifier/centroid classifier

This is a simple classification strategy. First the mean vector for each category is determined from the average DN in each band for each class. Computing the distance from its spectral position to each of the means and assigning it to the class with the closest mean can then classify an unknown pixel. One limitation of this technique is that it overlooks the different degrees of variation.

Parallelpiped classifier

This technique is also known as box classifier. The training information needed by this classifier for each of *k* classes specified is an estimate of minimum and maximum value on each of *p* bands or features. Alternatively, a range expressed in terms of a given number of standard deviation units on either side of mean of each feature can be used. Each unknown pixel is assigned to class in which parallelepiped it lies. Two other outcome of classifier are 1) that a pixel lies outside all parallelepiped, and 2) it lies inside two or more overlapping parallele-pipeds. In the first case the pixel is labelled as "unclassified". In the second case, the conflict is resolved by assigning it to any arbitrary class or Euclidean distance is computed between the pixel and centre point of each parallele-piped and "minimum distance" rule is used to label a class.

Gaussian maximum likelihood classifier

Gaussian maximum likelihood classifier is one of the most used classifiers in supervised classification. It uses variance and covariance of the spectral signatures of training classes to derive probable density functions for all the classes. It then uses these functions to compute the probability of the pixel value belonging to each class. After this a pixel is assigned to a class for which it has the highest probability value, which is considered as most likely class.

Post-classification smoothing

Classified image often has a salt and pepper appearance due the presence of scattered unclassified pixels, presence of very small classes, misclassification between confusion classes etc. In such situations some filtering is performed to remove the scattered pixels and produce classified image showing predominant classes in the scene.

Output

Output is generated in three common formats including hardcopy, tabular data, and digital information format.

Hardcopy

Coloured or B&W hardcopies are generated displaying thematic maps. These can also include enhancements, image annotation, classification legends, vectors superimposed on the thematic maps etc.

Tabular data

Tabular data represents statistics on the aerial extent of cover types present in an area or scene. The statistics are computed based on total number of pixels in a class and the ground area under each pixel.

Digital information format

With digital information format, the classified image can be exported in GIS compatible image formats and integrated directly with other collateral information for further analysis and integration.

Accuracy estimation

Once this classification step has been completed, it is important to determine the degree of error in the end product or accept a classification output if it meets a specified degree of accuracy. The procedures of accuracy estimation are based on building a square k x k matrix for specified k classes, called a "confusion" or "error" matrix. Error matrices compare, on a category-by-category basis, the relationship between known reference data (ground truth) and the corresponding results of classification. The overall accuracy is calculated by dividing the total number of correctly classified pixels by the total number of reference pixels.

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GEOGRAPHIC INFORMATION SYSTEMS (GIS)

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GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Introduction

This chapter focuses on the use of GIS in forestry in British Columbia (BC). It is meant as a source of reference material that has been selected from the much wider field of GIS applications in resource management. Even within the discipline of Forestry, this is quite selective as the BC Ministry of Forests' (BCMoF) database by itself would take many chapters to describe.

This chapter is organized around six topics; historical development, basic GIS concepts, GPS, digital data sources, attribute data and GIS analysis and modeling. The main purpose of this chapter is to provide reference material on GIS data, what is currently available for BC and the errors and accuracy of that data. There are two diversions from this data theme; a history of GIS to give some context to our current position in the development of GIS, and a quick look at some basic GIS analyses and modeling.

Historical Development

The use of mapping to detail complex arguments, and complex programs, has a very long history. In the late 1600s, for example, Filipo Arrieta mapped the deployment of troops he used to enforce a plague quarantine in the province of Bari, Italy (Koch, 2005); In the late 1700s researchers were mapping yellow fever outbreaks in New York city in an attempt to discover the source of the outbreak. By the mid 1800s, as Arthur H. Robinson shows in his Early Thematic Mapping in the History of Cartography (1982), mapping was a commonly employed tool for the analysis of everything from rail networks to the sources of meat supplied by French producers to the Paris market. The mid-19th Century "Atlas to Accompany the Second Report of the Irish Railway Commissioners" showed population, traffic flow, geology and topography superimposed on the same base map.

This work was not simply descriptive but typically analytic, often arguing a thesis through the graphic juxtaposition of elements (Koch, 2005). Perhaps the most famous nineteenth century example of this is the work of Dr. John Snow. In 1854 he mapped the locations of death by cholera in a central London area and used the map to argue its source was contaminated well water.

Across the nineteenth century a number of things together permitted the rapid advance of analytic cartography. The first was the growing use of statistics in disciplines that were to become social sciences. These statistics were employed by researchers in the maps they made. Secondly, improvements in printing permitted better illustrations to be made ever more cheaply for publications with larger and larger production runs. There was, in effect, a market not simply for maps but for maps as part of the evolving science and economics of the day.

After the Second World War other factors came together to create a computerized cartographic to advance mapped analysis. These included the development of first mainframe and then desktop computer hardware, and the software that made it work. Printers improved dramatically permitting ever-greater detail in the maps that resulted. At the same time, computers permitted ever more complex mathematical processes to be automated so that computations that would have taken weeks came to take first days and then minutes and then seconds. As a result, there was a rapid advance in the ability of social scientists to quantify experiences and map the result. This computerization – statistical and cartographic at once – had real effect in the areas of, for example, anthropology, economic and social geography, and regional science. There was as well an increasing social awareness, education levels and mobility, and awareness of environmental problems.

The computerized advance in these areas was "just in time" to meet the needs of the evolving society they were designed to serve. Integrated transportation plans of 1960s in cities like Detroit and Chicago required integration of transportation information (routes, destinations, origins and time) resulting in maps of traffic flow and volume. Similarly, the need to understand the nature of epidemic disease led to a range of mapped initiatives that helped explain by the 1980s the diffusion of diseases like influenza and AIDS.

A whole generation of researchers found ways to advanced statistical methods, computer programming, and computer cartography in this early post-war period. Johnston (1983) notes that four researchers were critical to the period 1958-1961, each for his work in one area of the developments that resulted:

Nystuen: Fundamental spatial concepts – distance, orientation, connectivity. Nystuen formalized these in a way that had not been done before, making of them a "network" theory in which distance became not a simple measure but a sometimes complex outcome.

Tobler: Computer algorithms for map projections, computer cartography. Tobler was more than a programer writing algorithms but a thinker who saw clearly how computers could be programed to create a type of map whose content was analytic and formative rather than merely descriptive.

Bunge: Theoretical geography – geometric basis for geography – points, lines and areas. As both practitioner and theoretician, Bunge saw mapping as a critical tool in the understanding of the evolving city and the way in which it was perceived by the people who lived in it. He was both an urban theoretician and a social reformer for whom the map informed both the city's history and its lived reality.

Berry's Geographical Matrix of places by characteristics (attributes). For Berry overlaying maps of different themes permitted a better approach to systematic regional studies informed by the detailed consideration of data at one layer and its relation to that existing at other layers of his rich overlays.

In the mid 1960s Canadian Roger Tomlinson created Canada Geographic Information System (CGIS), giving us the acronym GIS. The original purpose of CGIS was to analyze the data collected by the Canada Land Inventory (CLI) and to produce statistics to be used in developing land management plans for large areas of rural Canada. The CLI created maps that produced classified land using various themes: soil capability for agriculture, recreation capability, capability for wildlife (ungulates), capability for wildlife (waterfowl), forestry capability, and present land use for shoreline. These maps were developed at map scales of 1:50,000 and used a simple rating scheme, 1 (best) to 7 (poorest), with detailed qualification codes.

CGIS provided critical elements of the conceptual and technical foundation of what has become the modern GIS system. These included, in a partial list, the use of scanning for input of high density area objects; the vectorization of scanned images; geographical partitioning of data into "map sheets" or "tiles"; partitioning of data into themes or layers; use of an absolute system of coordinates for the entire country; coding of area object boundaries by arc, with pointers to left and right area objects; separation of data into attribute and locational files; and the concept of an attribute table. CGIS was also the first "topological" system with planar enforcement in each layer, relationships between arcs and areas coded within the database. CGIS also implemented functions for polygon overlay, measurement of area, user-defined circles and polygons for query (Tomlinson, 1987).

In 1969, Jack Dangermond founded Environmental Systems Research Institute (ESRI) based on techniques and ideas developed at the Harvard Lab and elsewhere. Dangermond took the raster-based thinking then current at Harvard, melded it with more classical vector approaches and created an integrated mapping system. ARC/INFO was released in the early 1980s, a successful implementation of the CGIS idea of separate attribute and locational information stored in a single database. ARC/INFO advanced the CGIS contribution to create a successful marriage of a standard relational database management system (INFO) to handle attribute tables with specialized software to handle objects stored as arcs (ARC). While others developed their own vision of the integrated system ARC/INFO's "toolbox", command-driven, product-oriented user interface became perhaps the most successful. Its modular design, which has become ArcView and ArcGIS, allowed elaborate applications to be built.

In BC, two GIS software packages were developed to serve the forest industry in the late 1980s; PAMAP created by Dr. P. Halloway of the University of Victoria, and TerraSoft created by Mr. D. Lemco a UBC, Faculty of Forestry graduate. TerraSoft was eventually bought by PAMAP which in turn was purchased in the late 1990's by PCI Geomatics, a Canadian remote sensing software company.

My thanks to Dr. Tom Koch for his help revising this historical section.

Basic Concepts

GIS definition

In simplistic terms a GIS is a computer map or graphic connected to a table, such that every object on the map is connected to one unique row in the table. Each object on the map can therefore have descriptive information about it entered into the table.

GIS is defined by Burrough and McDonnel as a set of tools and a database system:

> "…a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a

particular set of purposes."

"database system in which most of the data are spatially indexed, and upon which a set of procedures operated in order to answer queries about spatial entities in the database".

Vector/raster

Vector and raster are the dominant data models in a GIS. A raster model has attribute information attached to grid cells or pixels. Entities are built in a vector model from primitives (points, lines, polygons). Entities have coordinates and a direction. Lines with direction are called vectors, hence the name vector model. Raster is faster but vector is more accurate.

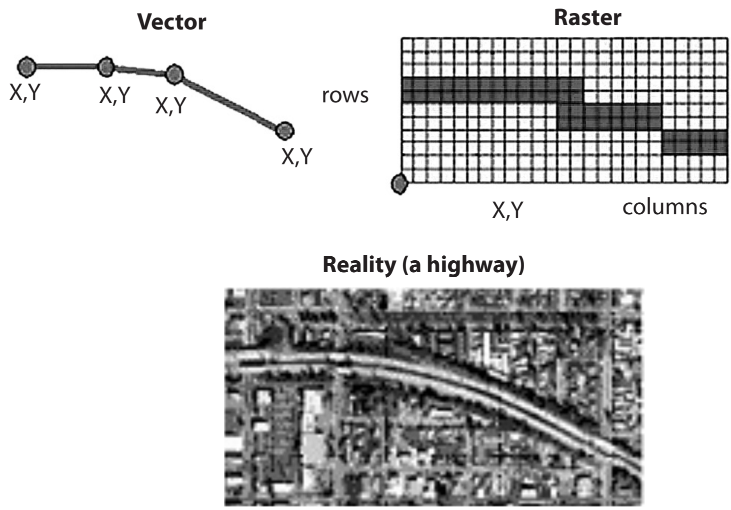


Figure 1: Vector vs. raster.

Topology

Topology is a set of rules that maintains a unique link between objects on a computer map and records in a data table. It is defined as the spatial relationships between adjacent or neighbouring features. Topology is important because it is an automated way to handle digitizing and editing errors as well as allowing for advanced analysis such as adjacency, connectivity and containment. Topology is implemented differently depending on the data structure. Figure 2 shows maps which model some aspect of the real world, in this case, forest polygons (part 1). Data (descriptive information) are collected about these forest polygons which is then entered into a table (part 2). Topology is added to the map which defines unique objects connected to individual rows in a table (part 3). The tabular data can then be linked to the topological table such that when one identifies a polygon on the map, the relative row in the descriptive data can be located.

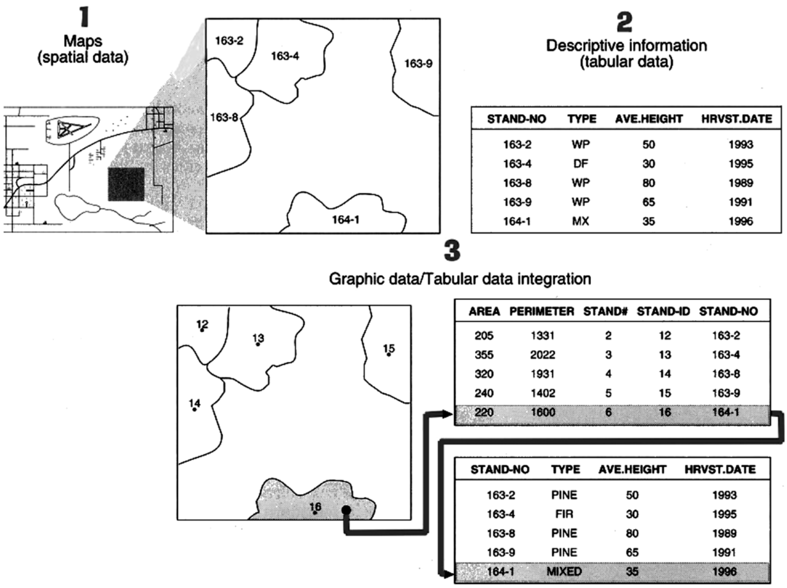


Figure 2: Topology.

Source: Adapted from ESRI's 1990. *Understanding GIS, PC Version*, Redlands, CA. p. 2-4.

Data structure

Our current GIS software programs from ESRI have three different data structures; shape files, coverages and geodatabases. Although ArcGIS can use all three data structures, the following work best with each program: ArcView uses shape files, ArcInfo uses coverages and ArcGIS uses geodatabases.

Shape files have a nontopological, simple data structure (SDS) that does not explicitly store topological relationships. It uses rings as non-self-intersecting loops that allow for fast display and many kinds of spatial analysis.

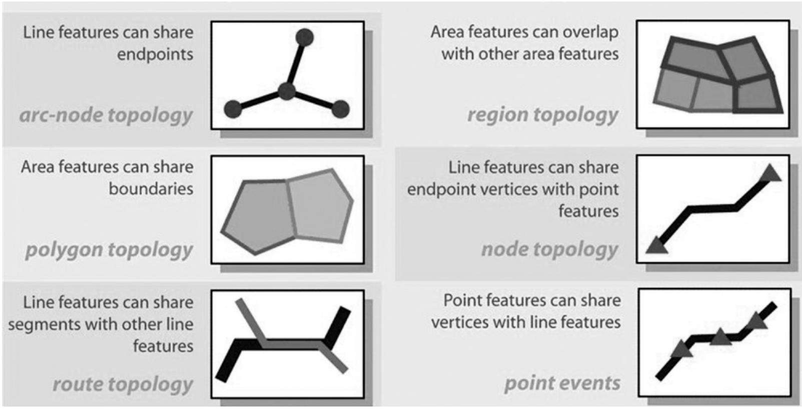
Coverages have a true topological data structure (TDS) that explicitly stores topological relationships. All forms of advanced spatial analysis are supported.

A geodatabase is a new data model where topology is created "on the fly" and both spatial and attribute data are stored in one relational data table. Topology is implemented as a set of integrity rules that define the behaviour of spatially related geographic features and feature classes. Figure 3 shows an example of the topology rules that might be applicable to simple data sets.

Projection

Geometric calculations use plane, orthogonal Cartesian coordinates which assume a flat plane. In order to do even simple area measurements, the curvature of the earth needs to be 'projected' onto a flat plane. The two projection systems used in BC are the Universal Transverse Mercator (UTM) and the Albers method. Both projections use the North American Datum from 1983 (NAD83).

UTM divides the earth up into 20 north-south zones. BC has 4 zones starting with zone 8 along the West Coast of the Queen Charlotte Islands and ending with



Source: *ESRI ArcNews*, Vol. 24 No. 2, Summer 2002.

Figure 3: Types of topology.

zone 11 along the Alberta border. Each zone has its own coordinate system such that the same X,Y position is repeated in each zone. Study areas that go across zones cannot use two zones. One zone has to be chosen and the areas in the second zone have to be artificially extrapolated from the first. Extrapolating one zone into another makes studying areas that cross zones difficult.

The BC government has changed all of its digital data to a variant of the Albers projection referred to as Canada Albers Equal Area Conic in ArcInfo's projection utility. Albers is as accurate as UTM but can be used across BC without dividing the province up into zones. The following projection values come from ESRI's BC Albers Equal Area Conic.prj file.

```
PROJCS["Canada_Albers_Equal_Area_Conic",
GEOGCS["GCS_North_American_1983",
DATUM["D_North_American_1983",
SPHEROID["GRS_1980",6378137,298.257222101]],
PRIMEM["Greenwich",0],
UNIT["Degree",0.0174532925199432955]],
PROJECTION["Albers"],
PARAMETER["False_Easting",0],
PARAMETER["False_Northing",0],
PARAMETER["Central_Meridian",-96],
PARAMETER["Standard_Parallel_1",50],
PARAMETER["Standard_Parallel_2",70],
PARAMETER["Latitude_Of_Origin",40],UNIT["Meter",1]]
```

Data errors

GIS gains much of its power from the ability to load and view many different data sets at the same time. Unfortunately, a dataset may have errors that a GIS cannot detect and these errors will propagate themselves through any analysis done with another dataset.

Another powerful feature of a GIS is the ease with which a dataset can be edited and updated. The problem comes from the inability to track these changes. A dataset which may have been accurate at one time, can be edited and passed on without the knowledge of its subsequent users.

Incorrect usage is also a problem. For example, data collected at one scale is then used at a finer scale that is outside the original data's accuracy limits. Or when data collected for one particular purpose is then used for another unrelated purpose. The only way to avoid these problems is to understand the lineage or development of the dataset. Metadata or data documentation must be obtained and reviewed to develop an understanding of the accuracy and precision of the dataset.

Table 1: Common sources of error encountered in using a GIS.

Stage	Sources of Error
Data Collection	Errors in field data collection
	Errors in existing maps used as source data
	Errors in the analysis of remotely sensed data
Data Input	Inaccuracies in digitizing caused by operator and equipment
	Inaccuracies inherent in the geographic feature (e.g. edges, such as forest edges, that do not occur as sharp boundaries
Data Storage	Insufficient numerical precision
	Insufficient spatial precision
Data Manipulation	Inappropriate class intervals
	Boundary errors
	Error propagation as multiple overlays are combined
	Slivers caused by problems in polygon overlay procedures
Data Output	Scaling inaccuracies
	Error caused by inaccuracy of the output device
	Error caused by instability of the medium
Use of Results	The information may be incorrectly understood
	The information may be inappropriately used

Source: Aronoff (1995).

Accuracy and precision

1. Accuracy is the degree to which information on a map or in a digital database matches true or accepted values. Accuracy is an issue pertaining to the quality of data and the number of errors contained in a dataset or map. In discussing a GIS database, it is possible to consider horizontal and vertical accuracy with respect to geographic position, as well as attribute, conceptual, and logical accuracy.
   - The level of accuracy required for particular applications varies greatly.
   - Highly accurate data can be very difficult and costly to produce and compile.
2. Precision refers to the level of measurement and exactness of description in a GIS database. Precise locational data may measure position to a fraction of a unit. Precise attribute information may specify the characteristics of features in great detail. It is important to realize, however, that precise data – no matter

how carefully measured – may be inaccurate. Surveyors may make mistakes or data may be entered into the database incorrectly.

- The level of precision required for particular applications varies greatly. Engineering projects such as road and utility construction require very precise information measured to the millimeter or tenth of an inch. Demographic analyses of marketing or electoral trends can often make do with less, say to the postal code or precinct boundary.
- Highly precise data can be very difficult and costly to collect. Carefully surveyed locations needed by utility companies to record the locations of pumps, wires, pipes and transformers cost $5-20 per point to collect.

High precision does not indicate high accuracy nor does high accuracy imply high precision. Beware of the dangers of false accuracy and false precision, that is reading locational information from a map to levels of accuracy and precision beyond that used to originally create the map. This is a problem with computer systems that allow users to freely pan and zoom to an infinite number of scales. Accuracy and precision are tied to the original map scale and do not change even if the user zooms in and out. Zooming can however mislead the user into falsely believing that the accuracy and precision have improved (see www.forestry.umt.edu/academics/courses/FOR503/GIS_Errors.htm for further information provided by Foote and Huebner, 2002).

Paper map resolution

Resolution is the degree to which closely related entities can be discriminated. Since a paper map is always the same size, its data resolution is tied to its scale. Resolution also limits the minimum size of features that can be stored. Generally, a line cannot be drawn much narrower than about 1/2 a millimetre. Therefore, on a 1:20,000 scale paper map, the minimum distance which can be represented (resolution) is about 10 metres. On a 1:250,000 scale paper map, the resolution is 125 metres.

GPS

Definition

A GPS receiver works by measuring the distance (range) from itself to a number of satellites and then through trilateration, determining its geographic location in latitude/longitude or UTM coordinates. The resultant location is accurate to about 10 metres but can be further refined to sub metre or even better using special methods such as differential correction. There are 24 satellites that provide 24-hour 3D coverage to most of the world except the extreme poles.

Positional accuracy

Positional accuracy is reduced by three main factors: selective availability, multi-path errors, and pseudorange errors. Each of these three factors is explained below and suggestions are made to avoid their effect on accuracy.

GPS terms

Differential correction is the process of massaging collected GPS data to remove the inaccuracies put in by pseudorange errors. At the same time you are collecting GPS data, there is another 'base station' collecting data at a known location. The differences between the GPS data collected at the base station and the known location of the base station are saved for you to correct your data. This can be done at a later date by downloading files and doing the calculation or by having a GPS unit that is capable of receiving this extra information directly from the base station and doing the calculation in 'real time'.

Selective availability (SA) is the deliberate degradation of accuracy by the US military in order to deny hostile users the full accuracy of GPS. Unprocessed GPS signals can only be accurate to 100 metres with selective availability turned on. Selective availability can be removed by differential correction. It has been turned off since the Spring of 2000.

Multipath errors occur when there is more than one apparent signal from the same satellite arriving at the GPS antenna. Additional signals come from reflections off nearby objects. This is of concern when receiving signals underneath the forest canopy or when surrounded by buildings or hills. Other sources of multipath errors are water surfaces or smooth ground, ductwork and roof top installations, and chain link fences and other metal lattice structures. Multipath errors can be reduced by collecting data for up to 10 minutes in one spot and averaging all data to one coordinate.

Pseudorange errors produce inaccurate measurements of the distance from a satellite to a receiver. They are caused by: inaccurate clock times on the satellite and the receiver; inaccurate location information about the satellite; and atmospheric interference with satellite signals. Pseudorange errors are quantified by the Position Dilution of Precision (PDOP) figure displayed on most receivers and can be reduced by planning data gathering (using an Almanac) during times of good satellite coverage (low PDOP).

Position dilution of precision (PDOP) is the sum of the errors introduced by satellite orientation. PDOP is composed of two pieces: HDOP or Horizontal Dilution of Precision (X,Y co-ordinates) and VDOP or Vertical Dilution of Precision (Z or elevation coordinates). The number of satellites and their position in the sky can be determined using an almanac. PDOP can be reduced by scheduling data collection in times of good satellite coverage and low PDOP. Good satellite coverage occurs when you can receive signals from at least four satellites and the satellites are spread in the sky fairly evenly. A good PDOP value when collecting data is 4, (this is a calculated value, not the number of satellites) an acceptable value is between 5 and 8, anything above 8 is of questionable accuracy unless many position fixes are averaged out to produce a single point.

Horizontal dilution of precision (HDOP) is for collecting 2-D or plane survey data. This is commonly the one used in forestry. It eliminates the need for Z or elevation data which makes data collection easier as elevation values are more difficult to obtain than X, Y values. It is common to use HDOP values of up to 8.0 when collecting forest polygon data as errors of 5 to 10 meters are acceptable when defining forest polygons.

Planning data collection

An **almanac** contains clock information as well as information about the orbital path for each satellite. The almanac tells you which satellites will be in your part of the world at a specific time and also what PDOP values to expect at that time. A GPS receiver can obtain new almanac information automatically every hour. This information needs to be downloaded to a computer to plan for your data collection.

Collecting data in the forest

Forest canopy produces many multi-path errors. These errors are caused by attenuation, obstruction and reflection. **Attenuation** is the weakening of the signal as it passes through the forest canopy. Attenuation is worst when the GPS signal is absorbed by water molecules in a very wet canopy. **Obstruction** occurs when the GPS line of sight signal is blocked by trees branches or leaves. **Reflection** of the GPS signal from trees, branches, leaves, and even the ground contribute to multi-path effects and inaccurate measurements.

These errors cannot be removed by differential correction. Multipath errors can only be removed manually using notes taken during data collection and professional judgement when editing the resultant GPS data.

Digital data sources

Digital data is required for GIS analysis. Each data set tries to model or simplify the world's complex interaction of objects and processes it into a number of separate themes or layers. Each theme is designed with a certain purpose in mind and the resultant data collection process is also designed to meet a particular purpose. Because data collection is very expensive and time consuming, a researcher is oten forced to use digital data in a way other than originally intended. It is therefore imperative to understand the limitations of existing digital data sources so that the data will not be used to do things it was never intended for.

An example of this is TRIM data, which provides the user with digital elevation points that can be used to create a 3-D model and from which contours can be derived. There is no built-in limitation to the contour interval that a researcher can create, although the data itself was only created to support contours 20 m apart. If contours are created closer together than 20 m, ridges and valleys will appear that do not actually exist and will mislead any other user of the data.

TRIM

The TRIM dataset covers all of BC in 7027, 1:20,000 map sheets. They are useful for resource managers in a number of areas such as: a base map for forest inventory; terrain mapping, and slope/terrain analysis. Each digital map contains contours, spot elevations, roads, rivers and cultural/political information. The contour interval is 20 m and the positional accuracy is plus/minus 10 m.

ARC/INFO layering scheme

When BC Environment translates the MOEP files into ARC/INFO, they are split into 10 layers:

tctr: Contours

tdem: Elevation points and break lines. All 3D lines are put into this layer, although Z-values on individual line vertices are ignored because ARC/INFO stores only 2D vertices.

tcul: Cultural features. Anthropogenic features such as buildings.

tcvr: Land Cover. Lines bounding wooded areas, grassland, etc.

tntl: Neatlines. Neatlines around 1:20,000, 1:50,000 mapsheet tiles.

tsrf: Surface features. Cliffs, scarps, eskers.

ttrn: Transportation. Roads, railway, pipelines, bridges.

ttxt: Text annotation. All text annotation.

twtr: Water features. Rivers, lakes, canals.

tmisc: Other features not in the above, and not useful for BC Environment's mandate. Photo centres.

In Figure 4 the Legend shows first the boundary or neat line of MKRF, then the ten TRIM layers with tdem as X's.

TRIM database uses alphanumeric codes to define map features. Figure 5 shows an example of the codes associated with one feature. The field FCODE or feature code contains the alphanumeric code for the map object. Figure 6 shows part of a file used to translate codes to meaningful descriptions of map objects. In this case, the map object is a river or stream.

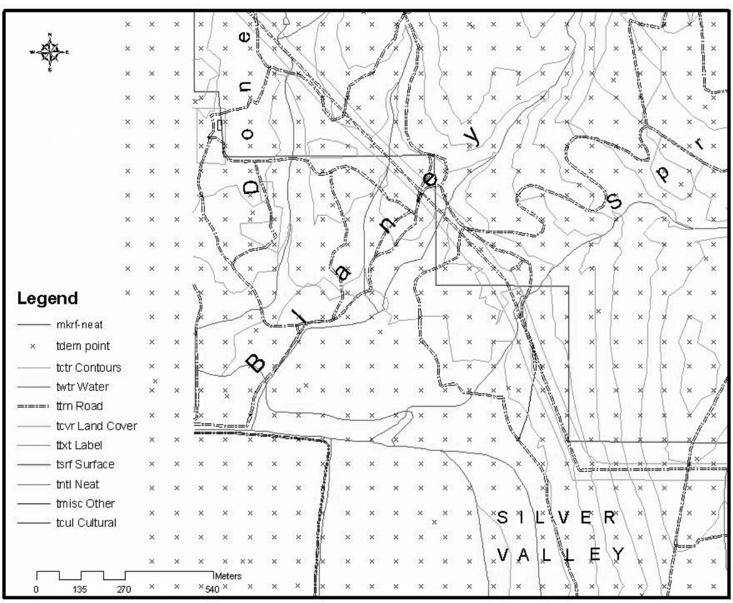


Figure 4: TRIM data at Malcolm Knapp Research Forest.

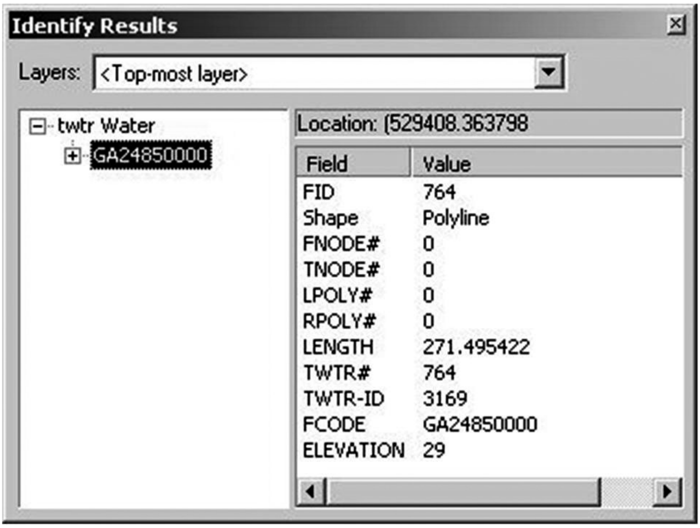


Figure 5: TRIM feature codes for a map object.

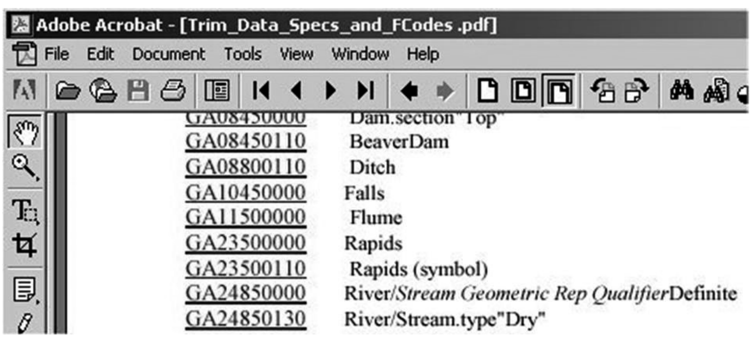


Figure 6: TRIM feature codes definitions.

BCMoF Forest Cover (FC)

The BC Ministry of Forests' FC dataset, in addition to being a comprehensive reference for forest species, age class, height class, site, and stocking level, also includes: land district boundaries, township boundaries, municipal boundaries, surveyed lots, main roads, secondary roads, logging and industrial roads, trails, railroads, flumes and ditches, pipelines, mines, lookouts, dams, post offices, and forest service offices. This information is separated into different layers or themes with associated attribute tables.

Before 2000 the FC theme was composed of two files known as FC1 and FIP. The FC1 file contained forest polygons and the FIP file was a database table describing

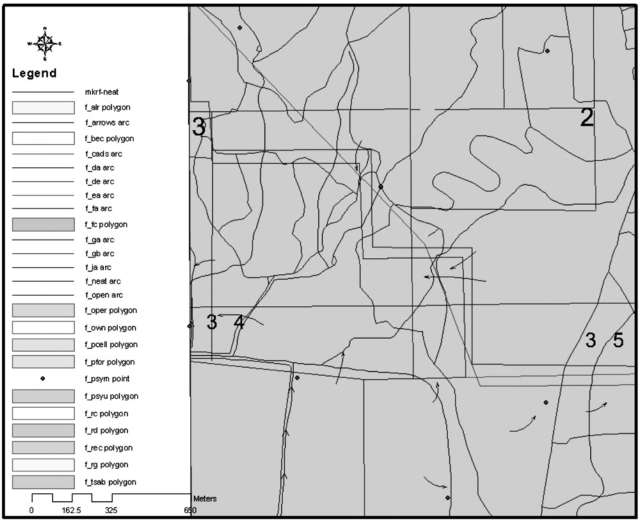


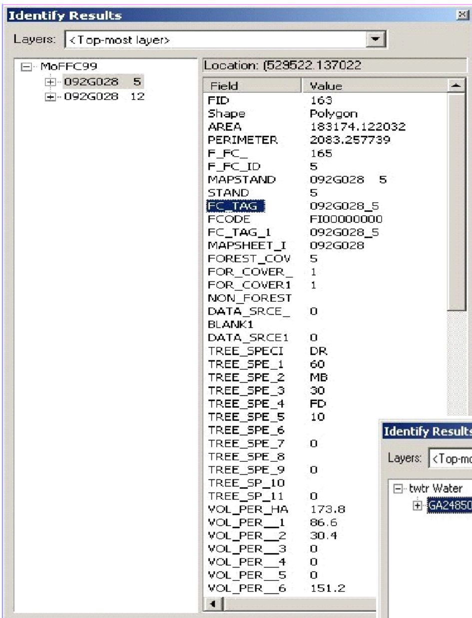
Figure 7: Forest Cover data to the border of Malcolm Knapp Research Forest.

the forest polygons. With a completion date of 2005, the Ministry of Sustainable Management (MSRM) will have created a data warehouse of all B.C. government land use and resource inventory information. Called the Land and Resource Data Warehouse (http://srmwww.gov.bc.ca/g/lrdw.html), this relational database will include FC data. The BCMoF's database is described in greater detail in the Attribute Data section of this chapter. For a complete description of the database table, see the BCMoF's Relational Data Dictionary web site (www.for.gov.bc.ca/pScripts/isb/idd/iddmain.asp).

The MoF's dataset uses TRIM as its base although it is only available for lands that are under the jurisdiction of the BCMoF. This does not include park, municipal or private land. BCMoF data assumes the same positional accuracy of plus/minus 10 m as TRIM with the smallest feature collected being greater than or equal to one hectare.

The BCMoF uses ESRI coverages in the form of spatial data layers. The attribute data files have to be downloaded separately from the Oracle database and joined to the spatial data. View http://srmwww.gov.bc.ca/gis/GISattrib.html for more information.

f_alr – Agriculture Land Reserves - Polygons from level 13
f_anno – Annotation Text - levels 5 6 7 8 10 14 16 51 61 and 63
f_arrows – Forest Cover Arrows - Arrow-Arcs on Level 19
f_bec – Biogeoclimatic zones - Polygons from level 25
f_da – Roads - Arcs with a DA FCODE
f_fa – Survyed Boundries - Arcs from level 7
f_fc – Forest Cover Polygons - Polygons from level 9
f_ga – Single Sided Water Features - Arcs with a GA FCODE
f_gb – Double Sided Water Features - Arcs with a GB FCODE
f_neat – Neat lines - Lines on level 62 or 56
f_oper – Operability Polygons - Polygons from level 54



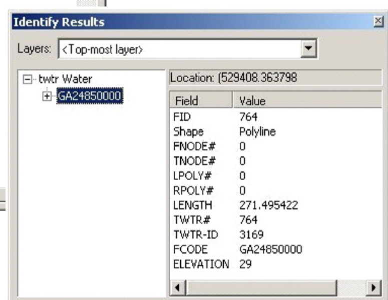


Figure 8:
Forest Cover codes for a map object.

f_own – Ownership - Polygons from level 31
f_pcell – Planning Cells - Polygons from level 24
f_pfor – Provincal Forests - Polygons from level 34
f_psym – Various Cell Symbols Cells from levels 6-8-15-18-53-51-63
f_psyu - Publicly Sustainable Yeild Units - Polygons from level 28
f_rc – Region Compartment - Polygons from level 23
f_rd – Region Disrtict - Polygons from level 33
f_rec – Recreation Resultant - Polygons from level 47
f_rg – Range - Polygons from level 43
f_tsab – Timber Supply Areas and Blocks - Polygons from level 27

Like TRIM data, Forest Cover data also has a FCODE field as shown in Figure 8, that is used to give more information about the map object. Unlike TRIM data however, this is also used to link to tables in an Oracle relational database in Victoria, BC, where much more information about the map objects are held and updated as new inventories are completed. In this case, forest vegetation polygons have additional descriptive information about tree species such as primary species (TREE_SPE_1) and primary species volume (VOL_PER_1) as shown in Figure 9. Unfortunately, there is no one place to easily determine the meaning of the various values within the fields, or the fields themselves. The BCMoF does have its Integrated Data Dictionary which can be viewed at www.for.gov.bc.ca/his/datadmin/idd_p.htm.

Canadian federal government

The federal government has a large range of free data available from their GeoGratis web site (www.geogratis.ca/geogratis/search?lang=en). GeoGratis is a web and file transfer protocol (ftp) site that distributes Canadian geospatial data. Vector mapping data is available in scales ranging from 1:250 000 to 1:30 000 000 in a variety of file formats. This includes Canada Land Inventory, LandSat7, RadarSat, National Atlas, Soil information, and many others. These data sets are selected samples as they are provided are provided to GeoGratis from both government and industry.

National topographic data base (NTDB)

The NTDB is a digital data base developed by Geomatics Canada. It covers the entire Canadian landmass and contains the features normally found on topographic maps at the scales of 1:50 000 and 1:250 000. This product includes thirteen themes including designated areas, general, hydrography, hypsography, manmade features, power network, rail network, relief and landform, road network, roads, toponymy, vegetation, and water saturated soils. Maps having all 13 themes and at a scale of 1:50 000 can be purchased through their website at www.cits.rncan.gc.ca/.

Ortho photos

BC has an on-going program to produce digital orthophoto mapping from new aerial photography based on TRIM 1:20 000 scale mapping. Orthophotos are created from aerial photographs, which are transformed to image maps by scanning, referencing and resampling the data based on terrain surface information. The result is an up-to-date digital file or hard copy map, which combines the benefits of line mapping for measuring distances and orienteering with the value of a photograph for visual interpretation. Digital data is priced by map sheet.

Remote sensing data

There are thousands of satellites orbiting the earth for various purposes. To view an animated representation of each satellite's position and name, visit NASA's web page and choose J-Track 3D (http://science1.nasa.gov/realtime/jtrack/3d/JTrack3D.html/).

Satellite data has to be processed before it can be used. There are different types of processing which result in different spectral resolutions (pixel size) and spatial accuracies (position on the ground). For more information on remotely sensed imagery and processing options view the RadarSat web site (www.rsi.ca/).

LandSat

LandSat data has been collected and archived since 1972. It is comprised of one panchromatic and seven multispectral bands of data, each approximately 35MB in file size. The first three bands cover the visible spectrum, bands 4, 5 and 7 are made up of portions of the infrared spectrum with band 6 covering the thermal spectrum. One full image covers an area approximately 180 km × 180 km.

Due to its spectral resolution, this data set is best used for detecting groups of objects rather than individual objects. It has been proven useful in forestry for detecting deciduous/coniferous trees, defining tree age classes, and finding trees attacked by insects.

IKONOS

IKONOS is high resolution imagery similar to ortho photos. It is made up of one panchromatic band, three visible spectrum bands and one infrared band. IKONOS can be used similarly to Landsat7, with the added benefit of higher resolution over smaller areas. This imagery is not archived and orders have to be done a month ahead of time and data collection is anytime within a 4 week 'window' unless extra fees are paid. As this is a side looking sensor, it becomes difficult to ortho rectify the image, especially in areas of high relief.

QuickBird

DigitalGlobe first launched this satellite in 2001. It is comprised of one panchromatic and four mulitspectral bands (B1 – blue, B2 – green, B3 – red, and B4 – near infrared). The pan-sharpened product combines the spectral information of the multispectral bands with the spatial information of the panchromatic band to produce in 70 cm: four bands in high resolution; or natural colour composite; or colour infrared composite. Like SPOT imagery, QuickBird offers higher resolution but fewer bands.

RadarSat-1

Unlike LandSat and IKONOS satellites that use passive sensors and cannot 'see' through clouds, forest canopy or ground, RadarSat uses a side looking, active sensor that sends out a signal and produces an image based on the return signal. This allows for imagery at any time of the day, in any weather conditions. Because of the angle of data collection, the imagery is not that good for highly mountainous terrain. It can be used for tree species identification and changes to the landform (harvesting).

SPOT

The French SPOT satellite was first launched in 1986 with SPOT 1. The current SPOT 5 was launched in 2002. Its optical imaging instrument is oblique-viewing, allowing frequent observations and stereoscopic imaging. It is comprised of one panchromatic and four multispectral bands of data. The multispectral bands are; B1 -green, B2 - red, B3 - near infrared, and B4 - short-wave infrared. By combining imagery from all five SPOT satellites, data can be generated at four levels of resolution (2.5, 5, 10 and 20 m) in black and white and in colour, and across the same 60 km swath.

Spot's 2.5 m colour imagery is very useful for monitoring and measuring vegetation although its cost and small number of multispectral bands have limited its use in British Columbia.

Table 2: Digital data comparisons.

Data Type	Scale	Spectral Resolution	Positional Accuracy	2005 $
TRIM	1:20,000	N/A	±10 m	400
Forest Cover	1:20,000	N/A	±25 m	250
NTS	1:250,000	N/A	±50 m	750
LANDSAT 7 Pan/	180 km ×	15 m		950
Multispectral/ Thermal	180 km	30 m 60 m	±50 m	
IKONOS Pan/				
Multispectral	100 sq km	1m to 4 m	±4.1 m	2,000
QuickBird Pan/		.6 m		
Multispectral	8 × 8 km	2.4 m	±7.7 m	8,000
RadarSat C Band	50 × 50 km	N/A		5,000
SAR Fine/Precision				
SPOT Pan/		2.5		
Multispectral	60 × 60 km	2.5 m to 20 m	±15 m	15,000

Note: These prices are for full data sets, and some data subsets can be purchased for less.

Attribute Data

Attribute data gives us more information about spatial objects. The three main types of attribute data are inventoried, modeled and derived.

Inventory data is collected in the field and manually entered into a database. An example is stand tree species, which was obtained from aerial photos by visual analysis.

Modeled data can use field data, but is projected into the future. Forest stand volume is an example of this and is measured by species in sample sites throughout the province. These data can then be applied to individual sites, fitting sample site growth curves to specific sites based on age and tree species of the specific stand.

The third type of attribute data are calculated or derived from existing data in the table. An example of this is the date the stand was established. This is calculated by subtracting the mean age of the leading species of the stand or plot (found in one field of the table) from the calendar year that the measurement or estimate was made (contained in another field of the table).

BCMoF codes on paper maps

Paper maps have a series of codes printed within or close by all stand polygons. These codes describe the stand characteristics within the polygon. The codes are:

ESA category: Environmentally Sensitive Area with a rating of High (E) Moderate (E2) or NR. High ratings have subscripts relating to soils (s) regeneration

(p) snow (a) recreation (r) wildlife (w) and harvesting/water (h). Moderate ratings have subscripts the same as above without snow and with an additional category snow/regen (c). The snow/regen category was only used from 1973 to 1975. The NR rating refers to management practices that are subject only to operational constraints consistent with the policies of the Forest Region.

Secondary element: There are three codes: L, S and V. L refers to a multi-layered stand (a separate description of each layer is available in the data base); S refers to a silvicultural component (a separate silviculture description is available in the forest cover database); and V refers to a veteran component.

Qualifier: There are also three codes for this: A, E, and I. A refers to a complex stand; E refers to an environmentally sensitive area, and I refers to an inoperable area.

Species composition: Species are listed in order of their percentage occurrence, with the dominant species first (e.g. F, A, Pl (Douglas-fir, trembling aspen, lodgepole pine).

Age class: Nine classes are broken into 20 year increments (Class 1: 1-20 years old, up to Class 9: 251 years+).

Height class: There are eight height classes (Class 1: 0-10.4 m; Class 2: 10.5-19.4 m; Class 3: 19.5-28.4 m; up to Class 8: 64+ m).

Stocking class: This is no longer used.

Site class: Indicates the ability of a site to produce commercial timber crops based on the estimated average height of the dominant trees of the leading species at age 50, and measured at breast height. Expressed as <10: NSR or non-productive; 10-17: poor; 18-30 medium, and 30+ as good.

Crown closure class: The amount of ground area covered by the canopy of trees, measured in 5 or 10% closure classes. A crown closure of 100% means that the crowns of the trees all touch, and this is referred to as a closed canopy. A crown closure of 50% has only half of the ground area covered by tree crowns, giving lots of room and time for growth before crowns touch.

History: The record of natural disturbances (e.g. fire, and pest infestation) and silviculture activities (e.g. site preparation, tree planting, and stand tending).

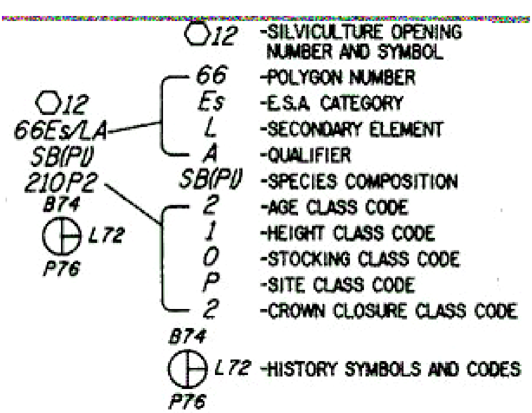


Figure 10: BCMoF paper map codes.

BCMoF relational data

Most introductory or desktop GIS software packages use 'flat file' data tables. This is a one-to-one relationship such that every object (point, line, polygon) on the map has only one record in the data table. When the user requires a one-to-many relationship to represent a series of changing values over time, a relational database management system (RDBMS) needs to be employed.

A RDBMS has the ability to access data organized in tabular files that can be related to each other by a common field. An RDBMS has the capability to recombine the data items from different files, providing powerful tools for data usage.

A relational database is a method of structuring data as collections of tables that are logically associated to each other by shared attributes. Any data element can be found in a relation by knowing the name of the table, the attribute (column or field) name, and the value of the primary key.

The BCMoF uses the Oracle relational database to store its attribute information. This is a part of the B.C. MSRM's Land and Resource Data Warehouse (LRDW) which contains land and resource information on all of B.C. To view a web version of this dataset go to http://maps.gov.bc.ca and choose "Land and Resource Data Warehouse Catalog".

The forest cover layer in the Oracle database, has a number of tables, each with an associated key field.

Table 3: Forest cover Oracle tables key fields.

Table Name	Key	IDD Definition
FIP_Version	Mapsheet_Id	Definition
FIP_History	FC_Tag, History_Layer, Attribute_Cd, Activity_Cd and Activity_Sub_Cd	
FIP_Polygon	FC_Tag	
FIP_Layer	FC_Tag and Forest_Cover_Layer_Cd	
FIP_Resultant	FC_Tag and Resultant_No	

Note: FC_Tag is a derived field from Mapsheet_Id and Forest_Cover_Polygon_Id.

BCMoF relational data dictionary

The attribute table associated with forest cover polygons has many descriptive fields with many values within each field. The values are often textual abbreviations or numbers representing ranges. In order to translate these coded values to meaningful information, a data dictionary can be used. The BCMoF has a limited data dictionary available at www.for.gov.bc.ca/pscripts/isb/idd/iddmain.asp.

BCMoF Oracle data warehouse and others

There are increasing numbers of centralized, data repositories for both public and government spatial data. These data warehouses allow users to access information about which data are available for a particular area and either purchase it or download it for free. This speeds up the process of discovering what data are available, what it contains, and where to obtain it.

The ESRI geography network is a good example of an internationally accessible data warehouse. The Geography Network is a global network of geographic information users and providers. It provides the infrastructure needed to enable the sharing of geographic information between data providers, service providers, and users around the world. The Internet is used to deliver geographic content to the user's browser and desktop. Through the Geography Network, you can access many types of geographic content including live maps, downloadable data, and more advanced services.

The Canadian National Forest Information System (NFIS) (http://nfis.org) data holding is a collection of natural resource data sets which have been developed by researchers in the Canadian Forest Service, and by provincial and territorial forest and environmental agencies. NFIS has implemented a spatial data warehouse to integrate, distribute and display these holdings in support of science and policy initiatives which must report on issues such as sustainable resource management, climate change and biodiversity.

The BCMoF maintains several of its corporate datasets in GIS data format, on a GIS "datacated" server. The data on this server, is available to all ministry staff who have an account. By providing this resource, the ministry has increased the efficiency, access and utilization of its data for spatial analysis. Spatial analysis is an integral part of the Ministry's strategic and operational planning functions. The data on this server can be used with such software tools as Arc/Info, Geomedia, Arcexplorer, and Arcview. Along with most other BC environmental data, BCMoF data can be accessed via Land Information BC with a BCe login. For further information go to http://maps.gov.bc.ca and click on forest mapview.

Structured query language (SQL)

SQL is used to communicate with a database, and it is the standard language for relational database management systems. SQL statements are used to perform tasks such as update data on a database, or retrieve data from a database. Some common relational database management systems that use SQL are Oracle, Sybase, Microsoft SQL Server, Access, and Ingres. Although most database systems use SQL, most of them also have their own additional proprietary extensions that are usually only used on their system. However, the standard SQL commands such as "Select", "Insert", "Update", "Delete", "Create", and "Drop" can be used to accomplish almost everything that is needed with a database. Source and SQL Interactive Tutorial on the web: www.sqlcourse.com/index.html.

GIS analysis and modeling

GIS analysis begins with an existing data set and transforms it depending upon the type of analysis undertaken. Data transformation can be as simple as saving the results of a query as a new data set, to complex multivariate statistical analysis. Buffering, overlaying, and 3-D analysis are common types of GIS analysis.

Spatial Analysis is defined by ESRI as: Analytical procedures applied with a GIS. There are three categories of spatial modeling functions that can be applied to geographic features within a GIS: (1) geometric models, such as calculating the Euclidean distance between features, generating buffers, calculating areas and perimeters, etc., (2) coincidence models, such as topological overlay; and (3) adjacency models (pathfinding, redistricting, and allocation). All three model categories support operations on spatial data such as points, lines, polygons, tins, and grids. Functions are organized in a sequence of steps to derive the desired information for analysis.

Although Geographical Information Systems have modeling tools, most special purpose spatial models run external to a GIS. Geographic data is developed to match the requirements of a model, exported to the model, the model is run, and sometimes the result is imported back into the GIS.

ArcGIS has ArcObjects that can be used with Visual Basic to access portions of ArcGIS's programming code directly. This has the potential of incorporating some special purpose spatial models within ArcGIS and gaining the benefits of having all the GIS tools available to the model.

Buffering

Buffering is a zone of a specified distance around coverage features. Both constant- and variable-width buffers can be generated for a set of coverage features based on the attribute values of each feature. The resulting buffer zones form polygons which are areas that are either inside or outside the specified buffer distance from each feature. Buffers are useful for proximity analysis (e.g. find all stream segments within 300 ft of a proposed logging area).

Overlay

An overlay is an analysis procedure for determining the spatial coincidence of geographic features. ArcInfo supports overlay among and between all feature classes.

Digital elevation models

A digital elevation model is a digital representation of a continuous variable over a two-dimensional surface by a regular array of z values referenced to a common datum. Digital elevation models are typically used to represent terrain relief. Also referred to as 'digital terrain model' (DTM).

Spatial statistics

Roger Bivand, in his 1998 article: A review of spatial statistical techniques for location studies, discusses spatial statistics:

> Spatial data analysis ranges from the visualization and exploration of spatial data, through spatial statistics to spatial econometrics. The techniques involved are intended to explore for and demonstrate the presence of dependence between observations in space. Typically, observations are classified into three broad types: fields or surfaces with values at least theoretically observable over the whole study area, as in geostatistics; point patterns representing the occurrence of an observation, such as reported cases in epidemiology; and lattice observations, where attribute values adhere to a tesselation of the study area. This last form has much in common with time series studies, and shares a number of key testing techniques with econometrics (Bivand, 1998).

Summary and Conclusion

Geographic Information Systems are a crucial part of resource management in British Columbia and around the world. They have moved from being a graphic display of tabular data to opening new ways of analyzing resource data i.e. 3-D modeling. Just recently GIS has made a significant move into the mainstream of data management by integrating the spatial or graphic data and tabular data within relational database management systems such as SQL Server and Oracle. This has significantly increased the ability of resource managers to control the data quality of natural resource databases.

Many different kinds of data models are now integrated within GIS. Surface modeling, statistical modeling, hydrological modeling, the list goes on. There are many tools available to link external models to GIS or recreate existing models within the GIS by accessing software libraries directly. The results of GIS analyses and modeling can also be easily shared across the internet.

As the power of GIS has increased so has the demand for training. Unfortunately, it is very easy to create misleading results if you do not know the quality of your data or the limitations of the analysis that you are undertaking. A number of organizations such as the Urban and Regional Information Systems Association (URISA) are implementing GIS certification as a way of determining standards for GIS professionals. This may simply be the maturing of a scientific field, but the significance is unmistakable: GIS users must have formal training in order to use this powerful tool successfully.

Acknowledgements

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Forest Engineering

FOREST ENGINEERING

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FOREST ENGINEERING

Introduction

Forest engineering is the application of basic engineering (civil, mechanical, industrial, etc.) to forest management and planning with due consideration to biotic, economic and environmental constraints. The scope of forest engineering is very broad and cannot be adequately covered in limited space. However, this handbook attempts to bring together some of the more useful tables, formulae and charts, which until now have been scattered in different technical publications and texts. Sample calculations have been provided where appropriate. Many of the "conventional" tables have been omitted in situations where a pocket calculator can be used to obtain the desired calculations from simple formulae. Some tables may not appear in the units desired by the reader (metric or Imperial), in such cases conversion units are noted.

Surveying

Slope calculations by table

The slope table (Table 1) included here is for Metric units. The table is a small sample of the standard lengthy tables found in handbooks, but can be used for any distance.

Example:

What is the HD (horizontal distance) and DE (difference in elevation) for a 364 m slope distance on a 12% slope?

Reading under the 30.0 column in Table 1 and the 12% slope row gives HD 29.8 and DE 3.6. Multiplying by a factor of 10, 300 m will then have HD and DE values of 298 and 36 respectively. Values for 60.0 m can be read directly from the table. Values for 4.0 m can be read as one tenth of the values obtained for 40.0 m provided in the table. Therefore the HD for 364 m is 298 + 59.6 + 3.97 = 361.57 m (all readings could be taken as feet from the same table if this were desired).

DE = 36 + 7.1 + 0.48 = 43.58 m

To calculate the difference in elevation (DE) between two points (AB). The following relationships hold:

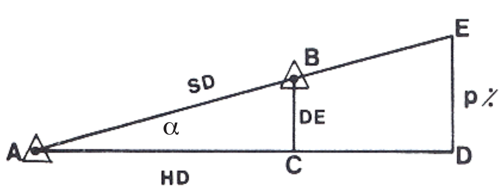


Figure 1: Difference in elevation between two points.

If AD = 100, then DE = p (%) = (HD) x $\frac{p\%}{100}$

DE = Difference in elevation or DE = SD • sinα

If slope distance (SD) and p% is known:

$$HD = \frac{SD}{\sqrt{1 + (p\%/100)^2}}$$ or HD = SD • cosα

If horizontal distance (HD) and p% is known:

$$SD = HD \sqrt{1 + \left(\frac{p\%}{100}\right)^2}$$ or $SD = \frac{HD}{\cos \alpha}$

To convert between degrees and slope percent use the following formulae (a pocket calculator can be used for tangent values):

slope percent (p%) = 100 x tan α degrees

slope angle in degrees (α) = arctan $\frac{p\%}{100}$

Stadia Calculations

Stadia measurements, made by surveying equipment with stadia hairs, are useful for providing topographic maps on rugged terrain where cross sectioning with level instruments is difficult (e.g. bridge site). The equipment is set up so that a wide area of the site can be seen. Levelling rods or stadia rods are then carried by the rod person to strategically locate points. The elevation, distance and position of these points in relation to the instrument is established by the stadia survey. The instrument's height is measured from the ground by tape or by putting the rod against the telescope. Stadia rods held vertically are then sighted by putting the middle hair on the same height as the instrument height. The vertical angle (α) is read and recorded. Then the intercept between the lower and the upper hair are read and recorded (see Figure 2).

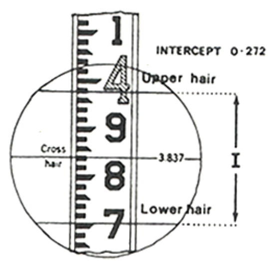


Figure 2: Rod-reading for stadia measurements.

From Table 2, the factor for the distance and elevation difference is read and the measured distances calculated by multiplying the table values with the intercept. The following equations show the theoretical basis for Table 2 and the calculations.

Horizontal distance: $HD = 100 \times \text{intercept} \times \cos^2 \alpha \; (+C)$

Difference in elevation: $VD = 100 \times \text{intercept} \times \frac{1}{2} \sin 2\alpha + C \times \sin \alpha$

(Note: C in most modern internal focusing instruments is zero).

Table 1: Horizontal distance (HD) and differences in elevation (DE) for various slope distances and percent Abney or clinometer readings.

PERCENT	SLOPE DISTANCE (m)																			
	10		20		30		40		50		60		70		80		90		100	
SLOPE	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.	H.D.	D.E.
1	10.0	0.1	20.0	0.2	30.0	0.3	40.0	0.4	50.0	0.5	60.0	0.6	70.0	0.7	80.0	0.8	90.0	0.9	100.0	1.0
2	10.0	0.2	20.0	0.4	30.0	0.6	40.0	0.8	50.0	1.0	60.0	1.2	70.0	1.4	80.0	1.6	90.0	1.8	100.0	2.0
3	10.0	0.3	20.0	0.6	30.0	0.9	40.0	1.2	50.0	1.5	60.0	1.8	70.0	2.1	80.0	2.4	90.0	2.7	100.0	3.0
4	10.0	0.4	20.0	0.8	30.0	1.2	40.0	1.6	50.0	2.0	60.0	2.4	69.9	2.8	79.9	3.2	89.9	3.6	99.9	4.0
5	10.0	0.5	20.0	1.0	30.0	1.5	40.0	2.0	49.9	2.5	59.9	3.0	69.9	3.5	79.9	4.0	89.9	4.5	99.9	5.0
6	10.0	0.6	20.0	1.2	29.9	1.8	39.9	2.4	49.9	3.0	59.9	3.6	69.9	4.2	79.9	4.8	89.8	5.4	99.8	6.0
7	10.0	0.7	20.0	1.4	29.9	2.1	39.9	2.8	49.9	3.5	59.9	4.2	69.8	4.9	79.8	5.6	89.8	6.3	99.8	7.0
8	10.0	0.8	19.9	1.6	29.9	2.4	39.9	3.2	49.8	4.0	59.8	4.8	69.8	5.6	79.7	6.4	89.7	7.2	99.7	8.0
9	10.0	0.9	19.9	1.8	29.9	2.7	39.8	3.6	49.8	4.5	59.8	5.4	69.7	6.3	79.7	7.2	89.6	8.1	99.6	9.0
10	10.0	1.0	19.9	2.0	29.9	3.0	39.8	4.0	49.8	5.0	59.7	6.0	69.7	7.0	79.6	8.0	89.6	9.0	99.5	10.0
11	9.9	1.1	19.9	2.2	29.8	3.3	39.8	4.4	49.7	5.5	59.6	6.6	69.6	7.7	79.5	8.7	89.5	9.8	99.4	10.9
12	9.9	1.2	19.9	2.4	29.8	3.6	39.7	4.8	49.6	6.0	59.6	7.1	69.5	8.3	79.4	9.5	89.4	10.7	99.3	11.9
13	9.9	1.3	19.8	2.6	29.7	3.9	39.7	5.2	49.6	6.4	59.5	7.7	69.4	9.0	79.3	10.3	89.2	11.6	99.2	12.9
14	9.9	1.4	19.8	2.8	29.7	4.2	39.6	5.5	49.5	6.9	59.4	8.3	69.3	9.7	79.2	11.1	89.1	12.5	99.0	13.9
15	9.9	1.5	19.8	3.0	29.7	4.5	39.6	5.9	49.4	7.4	59.3	8.9	69.2	10.4	79.1	11.9	89.0	13.4	98.9	14.8
16	9.9	1.6	19.7	3.2	29.6	4.7	39.5	6.3	49.4	7.9	59.2	9.5	69.1	11.1	79.0	12.6	88.9	14.2	98.7	15.8
17	9.9	1.7	19.7	3.4	29.6	5.0	39.4	6.7	49.3	8.4	59.2	10.1	69.0	11.7	78.9	13.4	88.7	15.1	98.6	16.8
18	9.8	1.8	19.7	3.5	29.5	5.3	39.4	7.1	49.2	8.9	59.1	10.6	68.9	12.4	78.7	14.2	88.6	15.9	98.4	17.7
19	9.8	1.9	19.6	3.7	29.5	5.6	39.3	7.5	49.1	9.3	58.9	11.2	68.8	13.1	78.6	14.9	88.4	16.8	98.2	18.7
20	9.8	2.0	19.6	3.9	29.4	5.9	39.2	7.8	49.0	9.8	58.8	11.8	68.6	13.7	78.4	15.7	88.3	17.7	98.1	19.6
21	9.8	2.1	19.6	4.1	29.4	6.2	39.1	8.2	48.9	10.3	58.7	12.3	68.5	14.4	78.3	16.4	88.1	18.5	97.9	20.6
22	9.8	2.1	19.5	4.3	29.3	6.4	39.1	8.6	48.8	10.7	58.6	12.9	68.4	15.0	78.1	17.2	87.9	19.3	97.7	21.5
23	9.7	2.2	19.5	4.5	29.2	6.7	39.0	9.0	48.7	11.2	58.5	13.4	68.2	15.7	78.0	17.9	87.7	20.2	97.5	22.4
24	9.7	2.3	19.4	4.7	29.2	7.0	38.9	9.3	48.6	11.7	58.3	14.0	68.1	16.3	77.8	18.7	87.5	21.0	97.2	23.3
25	9.7	2.4	19.4	4.9	29.1	7.3	38.8	9.7	48.5	12.1	58.2	14.6	67.9	17.0	77.6	19.4	87.3	21.8	97.0	24.3
26	9.7	2.5	19.4	5.0	29.0	7.5	38.7	10.1	48.4	12.6	58.1	15.1	67.7	17.6	77.4	20.1	87.1	22.6	96.8	25.2
27	9.7	2.6	19.3	5.2	29.0	7.8	38.6	10.4	48.3	13.0	57.9	15.6	67.6	18.2	77.2	20.9	86.9	23.5	96.5	26.1
28	9.6	2.7	19.3	5.4	28.9	8.1	38.5	10.8	48.1	13.5	57.8	16.2	67.4	18.9	77.0	21.6	86.7	24.3	96.3	27.0
29	9.6	2.8	19.2	5.6	28.8	8.4	38.4	11.1	48.0	13.9	57.6	16.7	67.2	19.5	76.8	22.3	86.4	25.1	96.0	27.9
30	9.6	2.9	19.2	5.7	28.7	8.6	38.3	11.5	47.9	14.4	57.5	17.2	67.0	20.1	76.6	23.0	86.2	25.9	95.8	28.7
31	9.6	3.0	19.1	5.9	28.7	8.9	38.2	11.8	47.8	14.8	57.3	17.8	66.9	20.7	76.4	23.7	86.0	26.6	95.5	29.6
32	9.5	3.0	19.0	6.1	28.6	9.1	38.1	12.2	47.6	15.2	57.1	18.3	66.7	21.3	76.2	24.4	85.7	27.4	95.2	30.5
33	9.5	3.1	19.0	6.3	28.5	9.4	38.0	12.5	47.5	15.7	57.0	18.8	66.5	21.9	76.0	25.1	85.5	28.2	95.0	31.3
34	9.5	3.2	18.9	6.4	28.4	9.7	37.9	12.9	47.3	16.1	56.8	19.3	66.3	22.5	75.7	25.8	85.2	29.0	94.7	32.2
35	9.4	3.3	18.9	6.6	28.3	9.9	37.8	13.2	47.2	16.5	56.6	19.8	66.1	23.1	75.5	26.4	84.9	29.7	94.4	33.0
36	9.4	3.4	18.8	6.8	28.2	10.2	37.6	13.5	47.0	16.9	56.5	20.3	65.9	23.7	75.3	27.1	84.7	30.5	94.1	33.9
37	9.4	3.5	18.8	6.9	28.1	10.4	37.5	13.9	46.9	17.4	56.3	20.8	65.7	24.3	75.0	27.8	84.4	31.2	93.8	34.7
38	9.3	3.6	18.7	7.1	28.0	10.7	37.4	14.2	46.7	17.8	56.1	21.3	65.4	24.9	74.8	28.4	84.1	32.0	93.5	35.5
39	9.3	3.6	18.6	7.3	27.9	10.9	37.3	14.5	46.6	18.2	55.9	21.8	65.2	25.4	74.5	29.1	83.8	32.7	93.2	36.3
40	9.3	3.7	18.6	7.4	27.9	11.1	37.1	14.9	46.4	18.6	55.7	22.3	65.0	26.0	74.3	29.7	83.6	33.4	92.8	37.1
41	9.3	3.8	18.5	7.6	27.8	11.4	37.0	15.2	46.3	19.0	55.5	22.8	64.8	26.6	74.0	30.3	83.3	34.1	92.5	37.9
42	9.2	3.9	18.4	7.7	27.7	11.6	36.9	15.5	46.1	19.4	55.3	23.2	64.5	27.1	73.8	31.0	83.0	34.9	92.2	38.7
43	9.2	4.0	18.4	7.9	27.6	11.9	36.7	15.8	45.9	19.8	55.1	23.7	64.3	27.7	73.5	31.6	82.7	35.6	91.9	39.5
44	9.2	4.0	18.3	8.1	27.5	12.1	36.6	16.1	45.8	20.1	54.9	24.2	64.1	28.2	73.2	32.2	82.4	36.2	91.5	40.3
45	9.1	4.1	18.2	8.2	27.4	12.3	36.5	16.4	45.6	20.5	54.7	24.6	63.8	28.7	73.0	32.8	82.1	36.9	91.2	41.0
46	9.1	4.2	18.2	8.4	27.3	12.5	36.3	16.7	45.4	20.9	54.5	25.1	63.6	29.3	72.7	33.4	81.8	37.6	90.8	41.8
47	9.1	4.3	18.1	8.5	27.2	12.8	36.2	17.0	45.3	21.3	54.3	25.5	63.4	29.8	72.4	34.0	81.5	38.3	90.5	42.5
48	9.0	4.3	18.0	8.7	27.0	13.0	36.1	17.3	45.1	21.6	54.1	26.0	63.1	30.3	72.1	34.6	81.1	38.9	90.2	43.3
49	9.0	4.4	18.0	8.8	26.9	13.2	35.9	17.6	44.9	22.0	53.9	26.4	62.9	30.8	71.8	35.2	80.8	39.6	89.8	44.0
50	8.9	4.5	17.9	8.9	26.8	13.4	35.8	17.9	44.7	22.4	53.7	26.8	62.6	31.3	71.6	35.8	80.5	40.2	89.4	44.7

51	8.9	4.5	17.8	9.1	26.7	13.6	35.6	18.2	44.5	22.7	53.5	27.3	62.4	31.8	71.3	36.3	80.2	40.9	89.1	45.4
52	8.9	4.6	17.7	9.2	26.6	13.8	35.5	18.5	44.4	23.1	53.2	27.7	62.1	32.3	71.0	36.9	79.8	41.5	88.7	46.1
53	8.8	4.7	17.7	9.4	26.5	14.0	35.3	18.7	44.2	23.4	53.0	28.1	61.9	32.8	70.7	37.5	79.5	42.1	88.4	46.8
54	8.8	4.8	17.6	9.5	26.4	14.3	35.2	19.0	44.0	23.8	52.8	28.5	61.6	33.3	70.4	38.0	79.2	42.8	88.0	47.5
55	8.8	4.8	17.5	9.6	26.3	14.5	35.0	19.3	43.8	24.1	52.6	28.9	61.3	33.7	70.1	38.6	78.9	43.4	87.6	48.2
56	8.7	4.9	17.5	9.8	26.2	14.7	34.9	19.5	43.6	24.4	52.4	29.3	61.1	34.2	69.8	39.1	78.5	44.0	87.3	48.9
57	8.7	5.0	17.4	9.9	26.1	14.9	34.8	19.8	43.4	24.8	52.1	29.7	60.8	34.7	69.5	39.6	78.2	44.6	86.9	49.5
58	8.7	5.0	17.3	10.0	26.0	15.1	34.6	20.1	43.3	25.1	51.9	30.1	60.6	35.1	69.2	40.1	77.9	45.2	86.5	50.2
59	8.6	5.1	17.2	10.2	25.8	15.2	34.5	20.3	43.1	25.4	51.7	30.5	60.3	35.6	68.9	40.7	77.5	45.7	86.1	50.8
60	8.6	5.1	17.1	10.3	25.7	15.4	34.3	20.6	42.9	25.7	51.4	30.9	60.0	36.0	68.6	41.2	77.2	46.3	85.7	51.4
61	8.5	5.2	17.1	10.4	25.6	15.6	34.1	20.8	42.7	26.0	51.2	31.2	59.8	36.5	68.3	41.7	76.8	46.9	85.4	52.1
62	8.5	5.3	17.0	10.5	25.5	15.8	34.0	21.1	42.5	26.3	51.0	31.6	59.5	36.9	68.0	42.2	76.5	47.4	85.0	52.7
63	8.5	5.3	16.9	10.7	25.4	16.0	33.8	21.3	42.3	26.7	50.8	32.0	59.2	37.3	67.7	42.6	76.1	48.0	84.6	53.3
64	8.4	5.4	16.8	10.8	25.3	16.2	33.7	21.6	42.1	27.0	50.5	32.3	59.0	37.7	67.4	43.1	75.8	48.5	84.2	53.9
65	8.4	5.4	16.8	10.9	25.2	16.3	33.5	21.8	41.9	27.2	50.3	32.7	58.7	38.1	67.1	43.6	75.5	49.0	83.8	54.5
66	8.3	5.5	16.7	11.0	25.0	16.5	33.4	22.0	41.7	27.5	50.1	33.1	58.4	38.6	66.8	44.1	75.1	49.6	83.5	55.1
67	8.3	5.6	16.6	11.1	24.9	16.7	33.2	22.3	41.5	27.8	49.8	33.4	58.2	39.0	66.5	44.5	74.8	50.1	83.1	55.7
68	8.3	5.6	16.5	11.2	24.8	16.9	33.1	22.5	41.3	28.1	49.6	33.7	57.9	39.4	66.2	45.0	74.4	50.6	82.7	56.2
69	8.2	5.7	16.5	11.4	24.7	17.0	32.9	22.7	41.2	28.4	49.4	34.1	57.6	39.8	65.8	45.4	74.1	51.1	82.3	56.8
70	8.2	5.7	16.4	11.5	24.6	17.2	32.8	22.9	41.0	28.7	49.2	34.4	57.3	40.1	65.5	45.9	73.7	51.6	81.9	57.3
71	8.2	5.8	16.3	11.6	24.5	17.4	32.6	23.2	40.8	28.9	48.9	34.7	57.1	40.5	65.2	46.3	73.4	52.1	81.5	57.9
72	8.1	5.8	16.2	11.7	24.3	17.5	32.5	23.4	40.6	29.2	48.7	35.1	56.8	40.9	64.9	46.7	73.0	52.6	81.2	58.4
73	8.1	5.9	16.2	11.8	24.2	17.7	32.3	23.6	40.4	29.5	48.5	35.4	56.5	41.3	64.6	47.2	72.7	53.1	80.8	59.0
74	8.0	5.9	16.1	11.9	24.1	17.8	32.2	23.8	40.2	29.7	48.2	35.7	56.3	41.6	64.3	47.6	72.3	53.5	80.4	59.5
75	8.0	6.0	16.0	12.0	24.0	18.0	32.0	24.0	40.0	30.0	48.0	36.0	56.0	42.0	64.0	48.0	72.0	54.0	80.0	60.0
76	8.0	6.1	15.9	12.1	23.9	18.2	31.8	24.2	39.8	30.3	47.8	36.3	55.7	42.4	63.7	48.4	71.7	54.5	79.6	60.5
77	7.9	6.1	15.8	12.2	23.8	18.3	31.7	24.4	39.6	30.5	47.5	36.6	55.5	42.7	63.4	48.8	71.3	54.9	79.2	61.0
78	7.9	6.2	15.8	12.3	23.7	18.5	31.5	24.6	39.4	30.8	47.3	36.9	55.2	43.1	63.1	49.2	71.0	55.4	78.9	61.5
79	7.8	6.2	15.7	12.4	23.5	18.6	31.4	24.8	39.2	31.0	47.1	37.2	54.9	43.4	62.8	49.6	70.6	55.8	78.5	62.0
80	7.8	6.2	15.6	12.5	23.4	18.7	31.2	25.0	39.0	31.2	46.9	37.5	54.7	43.7	62.5	50.0	70.3	56.2	78.1	62.5
81	7.8	6.3	15.5	12.6	23.3	18.9	31.1	25.2	38.9	31.5	46.6	37.8	54.4	44.1	62.2	50.4	69.9	56.6	77.7	62.9
82	7.7	6.3	15.5	12.7	23.2	19.0	30.9	25.4	38.7	31.7	46.4	38.0	54.1	44.4	61.9	50.7	69.6	57.1	77.3	63.4
83	7.7	6.4	15.4	12.8	23.1	19.2	30.8	25.5	38.5	31.9	46.2	38.3	53.9	44.7	61.6	51.1	69.3	57.5	76.9	63.9
84	7.7	6.4	15.3	12.9	23.0	19.3	30.6	25.7	38.3	32.2	45.9	38.6	53.6	45.0	61.3	51.5	68.9	57.9	76.6	64.3
85	7.6	6.5	15.2	13.0	22.9	19.4	30.5	25.9	38.1	32.4	45.7	38.9	53.3	45.3	61.0	51.8	68.6	58.3	76.2	64.8
86	7.6	6.5	15.2	13.0	22.7	19.6	30.3	26.1	37.9	32.6	45.5	39.1	53.1	45.6	60.7	52.2	68.2	58.7	75.8	65.2
87	7.5	6.6	15.1	13.1	22.6	19.7	30.2	26.3	37.7	32.8	45.3	39.4	52.8	45.9	60.4	52.5	67.9	59.1	75.4	65.6
88	7.5	6.6	15.0	13.2	22.5	19.8	30.0	26.4	37.5	33.0	45.0	39.6	52.5	46.2	60.1	52.9	67.6	59.5	75.1	66.1
89	7.5	6.6	14.9	13.3	22.4	19.9	29.9	26.6	37.3	33.2	44.8	39.9	52.3	46.5	59.8	53.2	67.2	59.8	74.7	66.5
90	7.4	6.7	14.9	13.4	22.3	20.1	29.7	26.8	37.2	33.4	44.6	40.1	52.0	46.8	59.5	53.5	66.9	60.2	74.3	66.9
91	7.4	6.7	14.8	13.5	22.2	20.2	29.6	26.9	37.0	33.7	44.4	40.4	51.8	47.1	59.2	53.8	66.6	60.6	74.0	67.3
92	7.4	6.8	14.7	13.5	22.1	20.3	29.4	27.1	36.8	33.9	44.2	40.6	51.5	47.4	58.9	54.2	66.2	60.9	73.6	67.7
93	7.3	6.8	14.6	13.6	22.0	20.4	29.3	27.2	36.6	34.1	43.9	40.9	51.3	47.7	58.6	54.5	65.9	61.3	73.2	68.1
94	7.3	6.8	14.6	13.7	21.9	20.5	29.1	27.4	36.4	34.2	43.7	41.1	51.0	47.9	58.3	54.8	65.6	61.6	72.9	68.5
95	7.2	6.9	14.5	13.8	21.7	20.7	29.0	27.5	36.2	34.4	43.5	41.3	50.7	48.2	58.0	55.1	65.2	62.0	72.5	68.9
96	7.2	6.9	14.4	13.9	21.6	20.8	28.9	27.7	36.1	34.6	43.3	41.6	50.5	48.5	57.7	55.4	64.9	62.3	72.1	69.3
97	7.2	7.0	14.4	13.9	21.5	20.9	28.7	27.9	35.9	34.8	43.1	41.8	50.2	48.7	57.4	55.7	64.6	62.7	71.8	69.6
98	7.1	7.0	14.3	14.0	21.4	21.0	28.6	28.0	35.7	35.0	42.9	42.0	50.0	49.0	57.1	56.0	64.3	63.0	71.4	70.0
99	7.1	7.0	14.2	14.1	21.3	21.1	28.4	28.1	35.5	35.2	42.6	42.2	49.7	49.2	56.9	56.3	64.0	63.3	71.1	70.4
100	7.1	7.1	14.1	14.1	21.2	21.2	28.3	28.3	35.4	35.4	42.4	42.4	49.5	49.5	56.6	56.6	63.6	63.6	70.7	70.7

Table 2: Horizontal distances and elevation differences for stadia readings.

Minutes		0	10	20	30	40	50	C = 1.00
0°	HD	100.00	100.00	100.00	99.99	99.99	99.98	1.00
	DE	0.00	0.29	0.58	0.87	1.16	1.45	0.01
1°	HD	99.97	99.96	99.95	99.93	99.92	99.90	1.00
	DE	1.74	2.04	2.33	2.62	2.91	3.20	0.03
2°	HD	99.88	99.86	99.83	99.81	99.78	99.76	1.00
	DE	3.49	3.78	4.07	4.36	4.65	4.94	0.04
3°	HD	99.73	99.69	99.66	99.63	99.59	99.55	1.00
	DE	5.23	5.52	5.80	6.09	6.38	6.67	0.06
4°	HD	99.51	99.47	99.43	99.38	99.34	99.29	1.00
	DE	6.96	7.25	7.53	7.82	8.11	8.40	0.08
5°	HD	99.24	99.19	99.14	99.08	99.03	98.97	1.00
	DE	8.68	8.97	9.25	9.54	9.83	10.11	0.10
6°	HD	98.91	98.85	98.78	98.72	98.65	98.58	0.99
	DE	10.40	10.68	10.96	11.25	11.53	11.81	0.11
7°	HD	98.51	98.44	98.37	98.30	98.22	98.14	0.99
	DE	12.10	12.38	12.66	12.94	13.22	13.50	0.13
8°	HD	98.06	97.98	97.9	97.82	97.73	97.64	0.99
	DE	13.78	14.06	14.34	14.62	14.90	15.17	0.15
9°	HD	97.55	97.46	97.37	97.28	97.18	97.08	0.99
	DE	15.45	15.73	16.00	16.28	16.55	16.83	0.17
10°	HD	96.98	96.88	96.78	96.68	96.57	96.47	0.98
	DE	17.10	17.37	17.65	17.92	18.19	18.46	0.18
11°	HD	96.36	96.25	96.14	96.03	95.91	95.79	0.98
	DE	18.73	19.00	19.27	19.54	19.80	20.07	0.20
12°	HD	95.68	95.56	95.44	95.32	95.19	95.07	0.98
	DE	20.34	20.60	20.87	21.13	21.39	21.66	0.22
13°	HD	94.94	94.81	94.68	94.55	94.42	94.28	0.97
	DE	21.92	22.18	22.44	22.70	22.96	23.22	0.23
14°	HD	94.15	94.01	93.87	93.73	93.59	93.45	0.97
	DE	23.47	23.73	23.99	24.24	24.49	24.75	0.25
15°	HD	93.30	93.16	93.01	92.86	92.71	92.56	0.96
	DE	25.00	25.25	25.50	25.75	26.00	26.25	0.27
16°	HD	92.40	92.25	92.09	91.93	91.77	91.61	0.96
	DE	26.50	26.74	26.99	27.23	27.48	27.72	0.28
17°	HD	91.45	91.29	91.12	90.96	90.79	90.62	0.95
	DE	27.96	28.20	28.44	28.68	28.92	29.15	0.03
18°	HD	90.45	90.28	90.11	89.93	89.76	89.58	0.95
	DE	29.39	29.62	29.86	30.09	30.32	30.55	0.32
19°	HD	89.40	89.22	89.04	88.86	88.67	88.49	0.94
	DE	30.78	31.01	31.24	31.47	31.69	31.92	0.33
20°	HD	88.30	88.11	87.93	87.74	87.54	87.35	0.94
	DE	32.14	32.36	32.58	32.80	33.02	33.24	0.35

Minutes		0	10	20	30	40	50	C = 1.00
21°	HD	87.16	86.96	86.77	86.57	86.37	86.17	0.93
	DE	33.46	33.67	33.89	34.10	34.31	34.52	0.37
22°	HD	85.97	85.76	85.56	85.36	85.15	84.94	0.92
	DE	34.73	34.94	35.15	35.36	35.36	35.76	0.38
23°	HD	84.73	84.52	84.31	84.10	83.89	83.67	0.92
	DE	35.97	36.17	36.37	36.57	36.77	36.96	0.40
24°	HD	83.46	83.24	83.02	82.80	82.58	82.36	0.91
	DE	37.16	37.35	37.54	37.74	37.93	38.11	0.41
25°	HD	82.14	81.92	81.69	81.47	81.24	81.01	0.90
	DE	38.30	38.49	38.67	38.86	39.04	39.22	0.43
26°	HD	80.78	80.55	80.32	80.09	79.86	79.62	0.89
	DE	39.40	39.58	39.76	39.93	40.11	40.28	0.45
27°	HD	79.39	79.15	78.92	78.68	78.44	78.20	0.89
	DE	40.45	40.62	40.79	40.96	41.12	41.29	0.46
28°	HD	77.96	77.72	77.48	77.23	76.99	76.74	0.88
	DE	41.45	41.61	41.77	41.93	42.09	42.25	0.48
29°	HD	76.50	76.25	76.00	75.75	75.5	75.25	0.87
	DE	42.40	42.56	42.71	42.86	43.01	43.16	0.49
30°	HD	75.00	74.75	74.49	74.24	73.99	73.73	0.86
	DE	43.30	43.45	43.59	43.73	43.87	44.01	0.51

HD = Horizontal Distance DE = Difference in Elevation

Distance and elevation is recorded on the sketch in the field book. The rod person moves to next point. The instrument person measures the horizontal angle to the new point and the process above is repeated. Then the points are mapped and contourlines interpolated. The selected points should mark terrain-slope change.

Example: Assume the elevation at the set up 268.2 m, the instrument height is 1.62 m, the rod intercept 1.45 m, the vertical angle = 12° 40’ down and C = 0. From Table 2, the horizontal distance is 95.19 × 1.45 = 138.03 m, and the difference in elevation: 21.39 × 1.45 = 31.02 m. The elevation of the observed point is: 268.20 – 31.02 = 237.18 m.

Working with Imperial units the rod should be in feet and tenths of feet. The intercept in feet multiplied by the table values will result in horizontal and vertical distances directly in feet.

Plotting Traverses

The most accurate method of plotting a traverse is to determine the latitude (north – south displacement) and departure (east – west displacement) of each station of the traverse. The displacement of each station is calculated from the horizontal distance and the bearing of the course connecting the station from the previous station. Normally, the Point of Commencement (PoC) is given a defined “x, y” (departure, latitude) coordinate and the subsequent courses are added to produce a coordinate for each station.

For latitudes (y coordinate), courses toward the north are positive; toward the south is negative. For departure (x coordinate), east is positive and west negative. Traverses in azimuths (direction stated as an angle between 0º and 360º) are very easy to calculate because the direction sign is provided by the calculator.
For a course of known horizontal distance (H) and azimuth (Aº):

Latitude = H cos Aº
Departure = H sin Aº

Traverses in "Bearings" state the angle of the course to the east or west of the North or South direction (e.g. N32W or S46E). Calculations using bearings can be more labor intensive, especially in assigning the positive or negative value of the course. A traverse table (Table 3) is often useful in assigning latitudes and departures. This table provides values for 0º to 45º reading from the top down, and for 45º to 90º reading from the bottom up.

Example:

A course runs N28ºW and is 132 meters in length.

From Table 3, at 28⁰ the Latitude	for 100 m is 88.3 m Departure is	–46.9 m
	for 30 m is 26.5 m	–14.1 m
	for 2 m is 1.77 m	–0.94 m
	Total 116.57 m	–61.94 m

Note that departure is negative because it runs westward.

Closure:

For a closed traverse, the sum of the latitudes and departures of all the courses should be zero. Closing error is calculated using the Pythagorean Theorem:

$$E = \sqrt{E_{lats}^{2} + E_{deps}^{2}}$$

The error $\frac{E}{\text{Total Traverse Length}}$ is expressed as a percent or as an accuracy ratio

$$1 : \left(\frac{\text{Total Traverse Length}}{E} \right)$$

Acceptable horizontal accuracy with basic hand held instruments ranges from 1:100 for field traverses to 1:300 for location surveys. For more critical surveys, more sophisticated equipment is used to obtain acceptable horizontal accuracy ranges up to 1:5000.

Adjusting closure:

If a traverse comes within an acceptable closing error, adjustments can be made to the coordinates of each station to eliminate the error. A common way of doing this is to adjust the latitude and departure for each leg using a prorate formula:

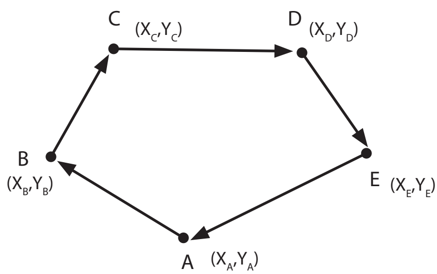
$$\text{Correction to Lat or Dep} = -\left(E_{\text{lat or dep}}\right)\frac{\text{Length of leg}}{\text{Total Traverse Length}}$$

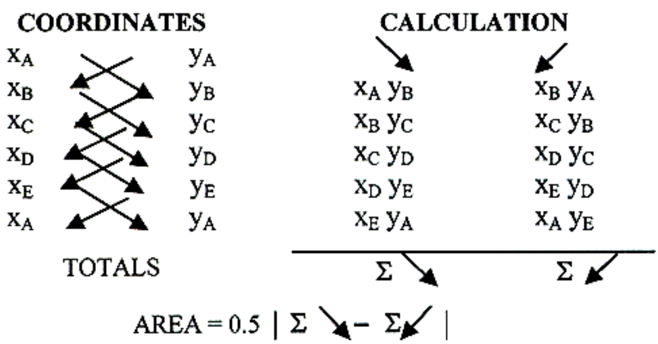
(Note the negative sign!)

Adjustments of this type do not actually correct errors. The error is systematically distributed over the survey to make it disappear on paper.

Calculating areas by coordinates

Once coordinates of a closed traverse are known, area can be quickly and precisely calculated using the area by coordinate method. The following example illustrates the setup of a calculation matrix that will work for any polygon. To close the calculation, the first coordinate **must** be repeated at the end. The direction of the traverse or the data entry does not matter, as long as it is in sequence.





The area is one half of the **absolute** value of the difference in the sums.

Note that it is extremely important to carry algebraic signs through all the calculations. Negative coordinates must carry their sign!

Another way to express this calculation (using numbered subscripts) for any polygon is:

$$\text{Area} = 0.5\,\left|(x_1y_2 + x_2y_3 + \ldots + x_ny_1) - (y_1x_2 + y_2x_3 + \ldots + y_nx_1)\right|$$

Where "n" is the last station.

Table 3: Traverse table for a quadrant compass.

Traverse Table: Latitudes and Departures

ANGLE (Read Down)	Horizontal Distance 10.0 Lat.	Dep.	20.0 Lat.	Dep.	30.0 Lat.	Dep.	40.0 Lat.	Dep.	50.0 Lat.	Dep.	60.0 Lat.	Dep.	70.0 Lat.	Dep.	80.0 Lat.	Dep.	90.0 Lat.	Dep.	100.0 Lat.	Dep.	
0	10.0	0.0	20.0	0.0	30.0	0.0	40.0	0.0	50.0	0.0	60.0	0.0	70.0	0.0	80.0	0.0	90.0	0.0	100.0	0.0	90
1	10.0	0.2	20.0	0.3	30.0	0.5	40.0	0.7	50.0	0.9	60.0	1.0	70.0	1.2	80.0	1.4	90.0	1.6	100.0	1.7	89
2	10.0	0.3	20.0	0.7	30.0	1.0	40.0	1.4	50.0	1.7	60.0	2.1	70.0	2.4	80.0	2.8	89.9	3.1	99.9	3.5	88
3	10.0	0.5	20.0	1.0	30.0	1.6	39.9	2.1	49.9	2.6	59.9	3.1	69.9	3.7	79.9	4.2	89.9	4.7	99.9	5.2	87
4	10.0	0.7	20.0	1.4	29.9	2.1	39.9	2.8	49.9	3.5	59.9	4.2	69.8	4.9	79.8	5.6	89.8	6.3	99.8	7.0	86
5	10.0	0.9	19.9	1.7	29.9	2.6	39.8	3.5	49.8	4.4	59.8	5.2	69.7	6.1	79.7	7.0	89.7	7.8	99.6	8.7	85
6	9.9	1.0	19.9	2.1	29.8	3.1	39.8	4.2	49.7	5.2	59.7	6.3	69.6	7.3	79.6	8.4	89.5	9.4	99.5	10.5	84
7	9.9	1.2	19.9	2.4	29.8	3.7	39.7	4.9	49.6	6.1	59.6	7.3	69.5	8.5	79.4	9.7	89.3	11.0	99.3	12.2	83
8	9.9	1.4	19.8	2.8	29.7	4.2	39.6	5.6	49.5	7.0	59.4	8.4	69.3	9.7	79.2	11.1	89.1	12.5	99.0	13.9	82
9	9.9	1.6	19.8	3.1	29.6	4.7	39.5	6.3	49.4	7.8	59.3	9.4	69.1	11.0	79.0	12.5	88.9	14.1	98.8	15.6	81
10	9.8	1.7	19.7	3.5	29.5	5.2	39.4	6.9	49.2	8.7	59.1	10.4	68.9	12.2	78.8	13.9	88.6	15.6	98.5	17.4	80
11	9.8	1.9	19.6	3.8	29.4	5.7	39.3	7.6	49.1	9.5	58.9	11.4	68.7	13.4	78.5	15.3	88.3	17.2	98.2	19.1	79
12	9.8	2.1	19.6	4.2	29.3	6.2	39.1	8.3	48.9	10.4	58.7	12.5	68.5	14.6	78.3	16.6	88.0	18.7	97.8	20.8	78
13	9.7	2.2	19.5	4.5	29.2	6.7	39.0	9.0	48.7	11.2	58.5	13.5	68.2	15.7	77.9	18.0	87.7	20.2	97.4	22.5	77
14	9.7	2.4	19.4	4.8	29.1	7.3	38.8	9.7	48.5	12.1	58.2	14.5	67.9	16.9	77.6	19.4	87.3	21.8	97.0	24.2	76
15	9.7	2.6	19.3	5.2	29.0	7.8	38.6	10.4	48.3	12.9	58.0	15.5	67.6	18.1	77.3	20.7	86.9	23.3	96.6	25.9	75
16	9.6	2.8	19.2	5.5	28.8	8.3	38.5	11.0	48.1	13.8	57.7	16.5	67.3	19.3	76.9	22.1	86.5	24.8	96.1	27.6	74
17	9.6	2.9	19.1	5.8	28.7	8.8	38.3	11.7	47.8	14.6	57.4	17.5	66.9	20.5	76.5	23.4	86.1	26.3	95.6	29.2	73
18	9.5	3.1	19.0	6.2	28.5	9.3	38.0	12.4	47.6	15.5	57.1	18.5	66.6	21.6	76.1	24.7	85.6	27.8	95.1	30.9	72
19	9.5	3.3	18.9	6.5	28.4	9.8	37.8	13.0	47.3	16.3	56.7	19.5	66.2	22.8	75.6	26.0	85.1	29.3	94.6	32.6	71
20	9.4	3.4	18.8	6.8	28.2	10.3	37.6	13.7	47.0	17.1	56.4	20.5	65.8	23.9	75.2	27.4	84.6	30.8	94.0	34.2	70

	Dep. 10.0	Lat. 10.0	Dep. 20.0	Lat. 20.0	Dep. 30.0	Lat. 30.0	Dep. 40.0	Lat. 40.0	Dep. 50.0	Lat. 50.0	Dep. 60.0	Lat. 60.0	Dep. 70.0	Lat. 70.0	Dep. 80.0	Lat. 80.0	Dep. 90.0	Lat. 90.0	Dep. 100.0	Lat. 100.0	ANGLE (Read Up)
21	9.3	3.6	18.7	7.2	28.0	10.8	37.3	14.3	46.7	17.9	56.0	21.5	65.4	25.1	74.7	28.7	84.0	32.3	93.4	35.8	69
22	9.3	3.7	18.5	7.5	27.8	11.2	37.1	15.0	46.4	18.7	55.6	22.5	64.9	26.2	74.2	30.0	83.4	33.7	92.7	37.5	68
23	9.2	3.9	18.4	7.8	27.6	11.7	36.8	15.6	46.0	19.5	55.2	23.4	64.4	27.4	73.6	31.3	82.8	35.2	92.1	39.1	67
24	9.1	4.1	18.3	8.1	27.4	12.2	36.5	16.3	45.7	20.3	54.8	24.4	63.9	28.5	73.1	32.5	82.2	36.6	91.4	40.7	66
25	9.1	4.2	18.1	8.5	27.2	12.7	36.3	16.9	45.3	21.1	54.4	25.4	63.4	29.6	72.5	33.8	81.6	38.0	90.6	42.3	65
26	9.0	4.4	18.0	8.8	27.0	13.2	36.0	17.5	44.9	21.9	53.9	26.3	62.9	30.7	71.9	35.1	80.9	39.5	89.9	43.8	64
27	8.9	4.5	17.8	9.1	26.7	13.6	35.6	18.2	44.6	22.7	53.5	27.2	62.4	31.8	71.3	36.3	80.2	40.9	89.1	45.4	63
28	8.8	4.7	17.7	9.4	26.5	14.1	35.3	18.8	44.1	23.5	53.0	28.2	61.8	32.9	70.6	37.6	79.5	42.3	88.3	46.9	62
29	8.7	4.8	17.5	9.7	26.2	14.5	35.0	19.4	43.7	24.2	52.5	29.1	61.2	33.9	70.0	38.8	78.7	43.6	87.5	48.5	61
30	8.7	5.0	17.3	10.0	26.0	15.0	34.6	20.0	43.3	25.0	52.0	30.0	60.6	35.0	69.3	40.0	77.9	45.0	86.6	50.0	60
31	8.6	5.2	17.1	10.3	25.7	15.5	34.3	20.6	42.9	25.8	51.4	30.9	60.0	36.1	68.6	41.2	77.1	46.4	85.7	51.5	59
32	8.5	5.3	17.0	10.6	25.4	15.9	33.9	21.2	42.4	26.5	50.9	31.8	59.4	37.1	67.8	42.4	76.3	47.7	84.8	53.0	58
33	8.4	5.4	16.8	10.9	25.2	16.3	33.5	21.8	41.9	27.2	50.3	32.7	58.7	38.1	67.1	43.6	75.5	49.0	83.9	54.5	57
34	8.3	5.6	16.6	11.2	24.9	16.8	33.2	22.4	41.5	28.0	49.7	33.6	58.0	39.1	66.3	44.7	74.6	50.3	82.9	55.9	56
35	8.2	5.7	16.4	11.5	24.6	17.2	32.8	22.9	41.0	28.7	49.1	34.4	57.3	40.2	65.5	45.9	73.7	51.6	81.9	57.4	55
36	8.1	5.9	16.2	11.8	24.3	17.6	32.4	23.5	40.5	29.4	48.5	35.3	56.6	41.1	64.7	47.0	72.8	52.9	80.9	58.8	54
37	8.0	6.0	16.0	12.0	24.0	18.1	31.9	24.1	39.9	30.1	47.9	36.1	55.9	42.1	63.9	48.1	71.9	54.2	79.9	60.2	53
38	7.9	6.2	15.8	12.3	23.6	18.5	31.5	24.6	39.4	30.8	47.3	36.9	55.2	43.1	63.0	49.3	70.9	55.4	78.8	61.6	52
39	7.8	6.3	15.5	12.6	23.3	18.9	31.1	25.2	38.9	31.5	46.6	37.8	54.4	44.1	62.2	50.3	69.9	56.6	77.7	62.9	51
40	7.7	6.4	15.3	12.9	23.0	19.3	30.6	25.7	38.3	32.1	46.0	38.6	53.6	45.0	61.3	51.4	68.9	57.9	76.6	64.3	50
41	7.5	6.6	15.1	13.1	22.6	19.7	30.2	26.2	37.7	32.8	45.3	39.4	52.8	45.9	60.4	52.5	67.9	59.0	75.5	65.6	49
42	7.4	6.7	14.9	13.4	22.3	20.1	29.7	26.8	37.2	33.5	44.6	40.1	52.0	46.8	59.5	53.5	66.9	60.2	74.3	66.9	48
43	7.3	6.8	14.6	13.6	21.9	20.5	29.3	27.3	36.6	34.1	43.9	40.9	51.2	47.7	58.5	54.6	65.8	61.4	73.1	68.2	47
44	7.2	6.9	14.4	13.9	21.6	20.8	28.8	27.8	36.0	34.7	43.2	41.7	50.4	48.6	57.5	55.6	64.7	62.5	71.9	69.5	46
45	7.1	7.1	14.1	14.1	21.2	21.2	28.3	28.3	35.4	35.4	42.4	42.4	49.5	49.5	56.6	56.6	63.6	63.6	70.7	70.7	45

Horizontal Distance

Road Engineering

Forest road design

Table 4 provides the basic design specifications for British Columbia forest roads. Additional specifications can be found in the Forest Practices Code “Forest Road Engineering Guidebook”.

Soil engineering

Soil is the building material of roads and its behaviour (engineering characteristics) should be understood by the forest engineer.

Table 5 is the guide for the identification of soil types in the United Soil Classification System and presents the most important parameters for different soil types for road construction and bridge foundation purposes.

Tables 6, 7 and 8 give numerical values for various soil characteristics of use in earth-pressure, earth-work and foundation safety calculations.

Table 4: Summary of alignment controls for forest roads.

Stabilized Road Width (m)	Design Speed (mn/h)	Minimum Stopping Sight Distance (m)[a]	Minimum Passing Sight Distance for 2 lane roads (m)	Minimum Radius of Curve (m)	Maximum Road Gradient[b]				
					Favorable		Adverse		
					Sustained	Short Pitch[c]	Sustained	Short Pitch[d]	Switch-backs
4	20	40	n/a	15	16%	18% for distance <150 m	9%	12% for distance <100 m	8%
5 to 6	30	65	n/a	35	12%	14% for distance <150 m	8%	10% for distance <100 m	8%
	40	95	n/a	65					
8+	50	135	340	100	8%	10% for distance <200 m	6%	8% for distance <100 m	6%
	60	175	420	140					
	70	220	480	190					
	80	270	560	250					

[a] Values of minimum stopping sight distance are applicable to single-lane two-way roads. For two-lane, and single-lane one-way roads, multiply the values of minimum stopping sight distance by a factor of 0.5.

[b] There are no absolute rules for establishing maximum road gradient. Maximum grades cannot generally be established without performing an analysis to determine the most economical grade for the site-specific conditions encountered. The maximum grade selected for design purposes may also depend on other factors such as: topography and environmental considerations; the resistance to erosion of the road surface material, and the soil in the adjacent drainage ditches; the life expectancy and standard of road, periods of use (seasonal or all-weather use), and road surfacing materials as it relates to traction; types of vehicles and traffic, and traffic volumes. Apply other grade restriction in special situations. For example:

- on horizontal curves sharper than 80 m radius, reduce the adverse maximum grade by 0.5% for every 10-m reduction in radius
- as required at bridge approaches, and at highway and railway crossings.

[c] Design maximum short-pitch favorable grades so that they are followed or preceded by a section of slack grade. The average grade over this segment of the road should be less than the specified sustained maximum.

[d] Design maximum short-pitch adverse grades as momentum grades.

Table 5:
Characteristics of soils groups for road construction (after FERIC, 2000)

USCS symbol	Value as subgrade	CBR value	Drainage properties	Erosion index	Frost susceptibility	Relative suitability as		
						Fill, no frost risk	Fill, frost risk	Surfacing
GW (well-graded gravel)	Excellent	60-80	Excellent	100	None to very slight	1	1	3
GP (poorly graded gravel)	Good to excellent	25-60	Excellent	100	None to very slight	3	3	-
GM (silty gravel)	Good to excellent	20-80	Fair to impervious	50-60	Slight to medium	4	9	5
GC (clayey gravel)	Good	20-40	Poor to impervious	70	Slight to medium	5	5	1
SW (well-graded sand)	Good	20-40	Excellent	80-90	None to very slight	2	2	4
SP (poorly graded sand)	Fair	10-25	Excellent	80-90	None to very slight	6	4	-
SM (sandy silt)	Fair to good	10-40	Fair to impervious	10-20	Slight to high	8	10	6
SC (sandy clay)	Fair to good	10-20	Poor to impervious	50	Slight to high	7	6	2
CH (high-plasticity inorganic clay)	Poor to very poor	3-5	Nearly impervious	50-60	Medium	13	8	-
CL (low plasticity inorganic clay)	Fair to poor	5-15	Nearly impervious	40	Medium to high	9	7	7
MH (inorganic high-plasticity silt)	Poor	3-8	Fair to poor	30-40	Medium to very high	12	13	-
ML (inorganic low- plasticity silt)	Fair to poor	10-20	Fair to poor	10-20	Medium to very high	10	11	-
OH (organic clay)	Poor to very poor	3-5	Nearly impervious	50	Medium	14	14	-
OL (organic silt)	Poor	4-8	Poor	30-40	Medium to high	11	12	-

Table 6:
General values of maximum dry unit weight (Standard Proctor) for coarse-grained backfill.

Backfill material	Unit weight, lb per cubic ft.	Unit weight, kg per cubic metre
GW	120 - 135	1.9 - 2.1
GP	110 - 125	1.8 - 2.0
GM	120 - 135	1.9 - 2.2
GC	110 - 130	1.8 - 2.1
SW	105 - 125	1.7 - 2.0
SP	100 - 120	1.6 - 1.9
SM	105 - 125	1.7 - 2.0
SC	100 - 125	1.6 - 2.0

Note: 1 lb = .4536 kg
1 cu.ft. = 0.0283 m^3

Table 7: Properties of earth and rock in construction.

Material	Percent swell	Swell factor
Clay, dry	35	0.74
Clay, wet	35	0.74
Earth, dry	25	0.80
Earth, wet	25	0.80
Earth and gravel	20	0.83
Gravel, dry	12	0.89
Gravel, wet	14	0.88
Limestone	60	0.63
Rock, well blastes	60	0.63
Sand, dry	15	0.87
Sand, wet	15	0.87
Shale	40	0.71

Note: Loose weight ÷ swell factor = Bank (in situ) weight
Approximately the same holds for volumes.

Table 8: Approximate allowable bearing pressures of foundation material.

Class of material	Allowable bearing pressure: Tons per sq. foot	Allowable bearing pressure: Tonnes per sq. metre
1. Massive igneous rocks and conglomerate, all in sound condition (sound condition allows minor cracks)	100	1000
2. Slate in sound condition (minor cracks allowed)	30	300
3. Siltstone, sandstone and cemented conglomerate in sound condition (minor cracks allowed)	10 - 40	100 - 400
4. Heavily shattered or weathered rocks	Site Specific	
5. Glacial till	10	100
6. Gravel, well-graded sand and gravel	2 - 6	20 - 60
7. Dense sand	3	30
8. Compact sand	1 - 3	10 - 30
9. Loose sand	< 1	< 10
10. Stiff clay	1.5 - 3	15 - 30
11. Firm clay	0.8 - 1.5	8 - 15
12. Soft clay	< 0.8	< 8
13. Compacted granular fill	2 to 5	20 –60

Note: 1 tonne per square metre = 0.000966 MPa
10 tonne per square metre = 1 ton per square foot

Sample Curve Calculation

Figure 4 represents a circular curve joining two tangents. I°, the deflection angle between the two tangents is measured. (The angle is bisected at V (Vertex) or PI (point of intersection) and O by the line OV, which also bisects the arc ADB and chord AB. OV is perpendicular to the chord AB at F). R (radius) is estimated to fit the curve to the terrain. Either the approximate start (or the end) of the curve can be estimated or its external distance DV. From the relationships below R can be found. If R is set, T & E are calculated.

T = AV = tangent distance

E = VD = external distance

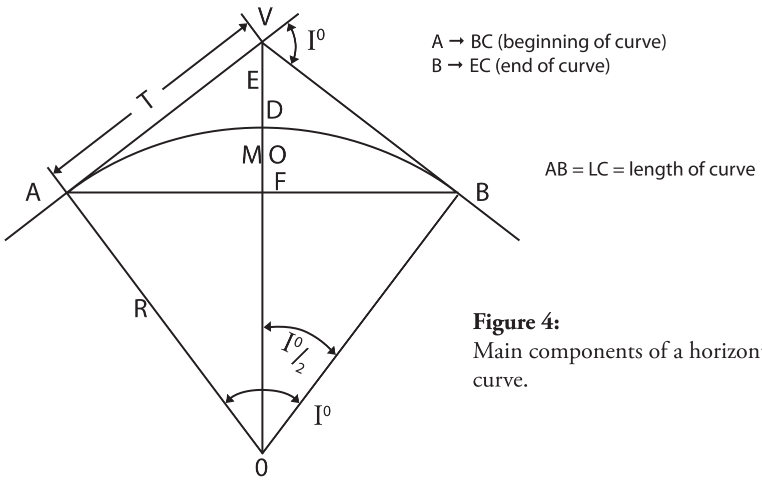


Figure 4:
Main components of a horizontal curve.

$$T = R \tan \frac{I^o}{2} = \text{tangent distance} = AV$$

$$E = R \sec \frac{I^o}{2} - R = R \left(\frac{1}{\cos \frac{I^o}{2}} - 1 \right) = \text{external distance} = DV$$

from triangle AOF, where AF = $\frac{1}{2}$LC

$$LC = 2R \sin \frac{I^o}{2} = \text{long chord} = AB$$

$$MO = R - R \cos \frac{I^o}{2} = R \left(1 - \cos \frac{I^o}{2} \right) = \text{middle ordinate} = DF$$

$$L = \frac{R I^o \pi}{180^o} = \text{curve length} = ADB$$

Example:

It is estimated that BC would be best about 80 m back from PI (V). Deflection angle was measured as 116°. What is the best fitting curve radius?

$80 = R \tan 58° = R(1.60) \therefore R = 50$ m

What are the measurements of this curve?

$$E = 50 \left(\frac{1}{\cos 58^o} - 1 \right) = 44.35 \text{ m}$$

LC = 84.80 m, M = 23.50 m, L = 101.23 m

Curve Layout by Deflection Angles from Station to Station (Moving Forward)

This is the most frequently used method. The BC is either established by measuring back T from PI, or the locator may decide to establish it during reconnaissance without establishing PI. After determining a best radius, the chord lengths are measured out with each course at a new azimuth. The rule to follow is:

The change in deflection angle at any station is the sum of half the central angle to the previous station plus half the central angle to the next station.

For any radius and any length of arc interval between stations (ℓ) the central angle (i^o) can be determined using the formula:

$$i^o = (57.3 / R)\ \ell$$

Often for the purpose of simplifying field work, radius is converted to a degree of curvature D^o based on a fixed arc length. For an arc length of 10m the above equation would be $D_{10}^o = 573/R\ \ell$

As long as arc lengths are kept reasonably short, the chord length is usually assumed to be equal for measuring in the field.

Example:

On a road centerline running an Azimuth of 10º a right curve is needed. A starting point (BC) is selected at 1+630. Selecting $D_{10}^o = 16^o$ for the first arc (10 m) and $D_{20}^o = 32^o$ for the remaining arcs (20 m) the Azimuths and angle changes are illustrated in Figure 5. The exit tangent from the curve has an azimuth of due east (90º)

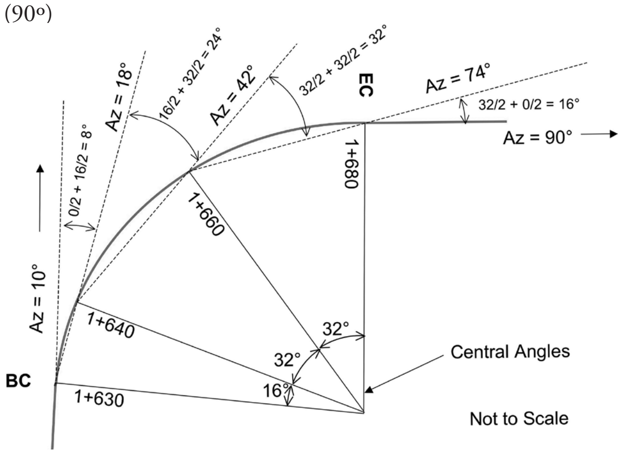


Figure 5: Curve layout by the deflection angle method.

Switchbacks

In addition to the curve layout, switchbacks need to consider the problem of reducing the steep road grade that results from having to turn the road directly down slope in the curve. This is accomplished by providing for a break in the surveyed grade before and after the curve portion of the switchback. Figure 6 and Table 9 provide guidelines for determining the length (Z) of level (0%) surveyed grade to provide for a switchback grade of 8%.

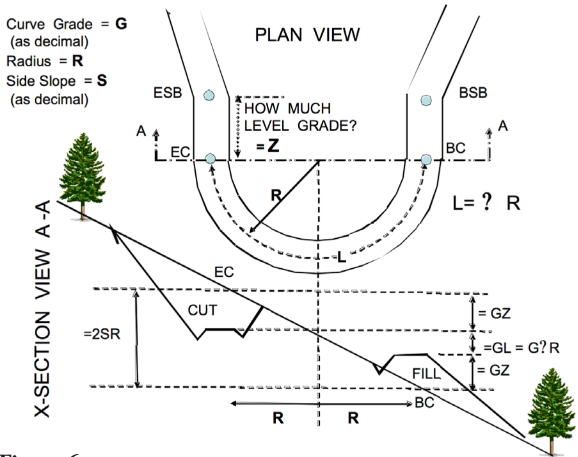


Figure 6:
Determining length of level grade before and after the curve portion of a switchback.

The formula used to determine Z is: $\frac{S\,R}{G} - \frac{\pi R}{2}$

Table 9: Extension (Z) of switchback curve to produce an 8% road grade.

Curve radius R	Side Slope (S) 14%	16%	18%	20%	22%	24%	26%	28%	30%	32%	34%	36%	38%	40%
16	2.9	6.9	10.9	14.9	18.9	22.9	26.9	30.9	34.9	38.9	42.9	46.9	50.9	54.9
18	3.2	7.7	12.2	16.7	21.2	25.7	30.2	34.7	39.2	43.7	48.2	52.7	57.2	61.7
20	3.6	8.6	13.6	18.6	23.6	28.6	33.6	38.6	43.6	48.6	53.6	58.6	63.6	68.6
22	3.9	9.4	14.9	20.4	25.9	31.4	36.9	42.4	47.9	53.4	58.9	64.4	69.9	75.4

Consideration must also be given to the vertical curve design. Sufficient road length is needed for transition of the grade of the switchback approaches to the grade of the switchback.

Earthworks

Geosynthetics

Geosynthetics are plastic materials that are used in earthworks, such as road construction, riprap revetments and retaining walls. Geotextiles and geogrids are types of geosynthetic used in applications to stabilize soils. Soil stabilization occurs through four basic functions of reinforcement, separation, filtration and drainage.

- Reinforcement involves strengthening the soil by inclusion of the geosynthetic that, with relatively small deformations, is tensioned and held in anchorage.

- Separation involves the prevention of intermixing of adjacent soils and rock, used as construction materials.
- Filtration involves the unimpeded flow of water across a geosynthetic, with little erosion or migration of soil particles.
- Drainage involves flow of water along or within the geosynthetic, where it acts as a conduit for preferential flow.

The relative importance of each basic function is governed by the site conditions, especially soil type and groundwater regime. The extent to which some or all of these functions are mobilized is governed by the construction application.

Construction survivability describes the ability of the geosynthetic to undergo site placement, without any significant damage, thereby ensuring it can function as intended over the service life of the installation. Hence, the required material properties of a geosynthetic on any project are largely determined by a combination of the intended basic function (s) and the requirements of construction survivability.

In case of routine engineering applications, the required material properties may be outlined in a standard specification document. A standard specification will reccomend default values for material properties, according to the type of project. Typically, a distinction is made between requirements for road construction, subsurface drainage, and erosion control. Alternatively, the required properties may be established with reference to specialist design guidance and site-specific design parameters. The latter approach is used for embankments, retaining walls and bridge abutments.

Selection of a suitable geosynthetic involves a comparison of the required material properties (for the project) and the available material properties (of the product). Manufacturers report the available material properties of each product in a technical data sheet. Those data typically describe general properties of the product, together with results of index tests to characterize the strength, hydraulic behaviour and durability. In design, the geosynthetic is selected on the basis that the available material properties meet or exceed the required properties. A review of forest engineering case studies shows the use of standard specifications for routine applications of geosynthetics to be very successful.

Forest Road Bridge Design

Arguably the most important activity in designing bridges for forest roads is determining where the bridge will be located. Considerations in locating forest road bridges include 1) the resources that the road is accessing, 2) the cost of constructing the approaches and the bridge structure, 3) effects on other forest resources such as water quality, and 4) future maintenance requirements. Properly locating a bridge can greatly reduce the cost and the impact on other forest resources; this is the responsibility of the forest planner who is designing the road and harvesting system for the area.

The joint practice board of the Association of Professional Engineers and Geoscientists of British Columbia and the Association of British Columbia Forest Professionals is preparing the final draft of the “Guidelines for Professional Services in the Forest Sector – Crossings". This document, if accepted by the ABCFP and APEGBC, will outline professional responsibility in Forest Road Bridge Design. Draft versions of this document are available on the ABCFP website (www.abcfp.ca)

In general, forest road bridge design will fall under the purview of a Professional Engineer with suitable experience. However, where risk assessment shows there is very low hazard and consequence, such as for gravel decked log culverts with single log cribs, it may be possible to use design tables such as those presented by Nagy *et al.* (1980) in the "Log Bridge Construction Handbook".

Logging General

Logging, as a complete system, involves falling timber, bucking, yarding, loading and trucking from the logged setting to a storage facility. It involves many techniques derived from a wide range of disciplines including engineering, economics, material handling and cable mechanics. Each of these topics would, ideally, require an individual handbook to adequately cover the subject.

In addtion to the traditional approach towards logging, some new planning techniques have been introduced. These include:

1. Engineering economics principles are used by the logging engineer to develop realistic dollar estimates for feasibility studies and production schedules. A reference textbook is: Riggs, James L. 1977. Engineering Economics. McGraw-Hill Ryerson Limited, Scarborough, Ontario.
2. Advanced statistics are used in the design of experiments, analyses of logging methods and machine performance ratings.
3. Optimization techniques, used in many industries for solving complex problems, are adaptable to applications in logging productivity analysis. A reference textbook is: Hillier and Lieberman, 2001, 7th edition. Introduction to Operations Research. McGraw Hill Inc., San Francisco, CA, USA.
4. Digital terrain models, used with desktop computers, provide the logging engineer with terrain and other data used in logging analysis, particularly in environmentally sensitive areas.
5. Modern desktop computers and programmable calculators can now provide on-site computing power as a basic tool for the logging engineer involved in the new planning techniques described above.

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General Information

THE FORESTRY PROFESSION

by

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The Association of BC Forest Professionals

THE FORESTRY PROFESSION

The History of the Forestry Profession in BC

The concept of managing forests to provide timber for a permanent forest products industry, as well as for water, flood control, wind breaks, wildlife habitat and other values came to North America via German forester Dr. Bernhard Fernow. His arrival in 1876 was opportune as public alarm was growing over the destruction of vast forests in the eastern United States and increasing shortages of timber products. Dr. Fernow brought with him a scientific basis for forest management for perpetual and multiple uses.

By the turn of the century this visionary conservationist had many disciples in government and academic positions in the United States. One of these was HR MacMillan, who became the first Chief Forester of BC. Dr. Fernow, after a distinguished career in the United States, became the first Dean of Forestry at the University of Toronto in 1908. Upon coming to Canada he presented compelling arguments on the need for forest management, and urged that because of the time involved to secure future benefits that the task be a state endeavour. This view, subsequently advocated by Fernows' many disciples, had a strong influence on the development of policies for the retention of forest land in public ownership.

In 1908 most of Canada's professional foresters, who numbered less than one dozen, met to establish the Canadian Society of Forest Engineers (CSFE). They did this despite the fact that Fernows' definition of what constituted forestry did not include engineering. In their minds the theory and practice of Forestry included soils, forest insects and diseases, protection from fire, reforestation, forest measurements and inventory. The work of the forester was to study, to understand, to protect, to restore and to manage the forest for a variety of purposes and uses. The tasks of developing, harvesting, transporting and processing were considered peripheral. Though small in number, these early foresters made a vital contribution to forestry through their dedication to conservation and their unbridled enthusiasm.

Fred Mulholland and Dick Orchard, both pioneers of the BC Forest Service, were key participants in BC professional forestry. Mulholland strongly advocated a mixture of public and private ownership of forests. He was an unusual civil servant in that he actively participated in open debate at a time when government employees were discouraged from participating in debates about public policy. The Daily Colonist called him an "active and inspired supporter of practical forestry, a fearless critic and a leader among his professional associates". He was a member of the Victoria Branch of the CSFE and its national president in 1940. He used this position to lobby fearlessly for change and sustained yield.

C.D. Orchard, BC's Deputy Chief Forester and Mulholland's superior, was also beginning to lobby his political masters for a major forest policy overhaul. It seems that Mulholland and the CSFE had a significant effect on Orchard's decision to draft forest legislation revisions designed to produce sustained yield.

In 1942, Orchard submitted a draft forestry bill suggesting fundamental forest policy changes to Premier John Hart's cabinet. In late 1943, Hart appointed Orchard as Chief Forester and as the principal assistant to the Sloan Commission on the state of BC's forests.

The work of pioneer foresters in the 1910-1945 period consisted mainly of protection from fire, insects and diseases and the continuing mapping and inventory of the resource. There were a few dedicated to research and reforestation but a lack of people and finances hindered progress.

Hindsight today shows it took roughly one working generation to begin to implement the sustained yield management concepts set forth in the 1912 *Forest Act.*

It was public ownership of forest land that triggered the need for a professional association with a mandate to protect the public interest in forest management. Mulholland was frustrated in his efforts to gain broader acceptance within the framework of the provincial legislation for professional engineers. Early in 1945 he circulated a draft professional forester's bill to a dozen influential forestry people. At the time there was a close working relationship between the government service, the university, the few foresters working in industry, and the Canadian Society of Forestry Engineers. It is interesting that the Act eventually passed in April, 1947 and was entitled *An Act Respecting the Practice of Forestry*. It defined the practice of forestry as follows:

> "Practice of Forestry" means advising, reporting upon, supervising, teaching, or making research in any branch of the administration or management of forests or forest land; and also the valuation, maintenance, conservation, protection, regeneration, and reforestation of forests and forest land, and the preparation of plans in connection with such matters.

The *Foresters Act* created the self-regulatory authority, the Association of British Columbia Forest Professionals (ABCFP) formerly known as The Association of British Columbia Professional Foresters. The Act gives the ABCFP the power to ensure that only those persons who meet the entrance and continuing competence requirements set by the Association are entitled to practice professional forestry or use the title Registered Professional Forester (RPF) or Registered Forest Technologist (RFT).

Rationale for Establishing a Professional Association

The following excerpt from the ABCFP President Mulholland's address at the first annual meeting, in 1949, reveals the rationale for establishing the Association.

> At this critical point in our forests' life, this Association has been established not by chance. If the forests are to be well managed, the people managing them must be competent. That is why there are forestry departments at universities and why there is a forestry

> profession. It seems to me that if foresters are to maintain a true professional status, such as is generally recognized in the medical and legal professions, it is essential that foresters first should recognize the individual responsibility of each member. Those in the industry and in private practice must recognize the responsibilities of their brethren in public service, and government foresters those of their brethren in the industry.

Speaking about the importance of professional independence, Mulholland said:

> There will be, and should be, professional competition; we will not all think alike. Nothing could be more harmful to forestry than attempts to impose schematic uniformity by force of the profession or of government. You should be free to manage your forest as you think best and I mine. If such freedom is to be justified, we will have to deserve it. This Association will have a part in maintaining the standard of forestry through its registering powers. They were given by the Legislature for this purpose.

Getting started

The first tasks of the charter members were to form a Council of management, appoint a registrar/secretary-treasurer, and appoint a Board of five examiners to review applications. F. Malcolm Knapp, RPF was registered as member number one and appointed registrar. He held this position for 25 years, the first seventeen of which he worked out of his office at the University of British Columbia. The Association owes him and the University much.

Charter member Hector Richmond, RPF recalls that "everybody under the sun wanted to join". He served on the committee that reviewed applications during the one-year grace period provided by the grandfather clause in the *Foresters Act*. He said it was fairly straightforward to determine who amongst the many applicants of timber cruisers, loggers, and practical foresters actually met the criteria established for appropriate education and experience.

Forester training and growth of the profession

The war had ended and it was a heady time. The University of British Columbia's Forestry Department was full of returning veterans, with 325 students enrolled and just seven full time instructors.

However, by 1951 enrolment had dipped to 90 and remained at a little over 100 for the next decade. The Faculty of Forestry graduated about 30 per year through the fifties, and about 45 per year through the sixties. These numbers were insufficient to meet the demand for foresters in the province. In the early to mid fifties there was also an outflow of government foresters to better paying industry positions: in 1956 alone 48 left the Forest Service for this reason.

Many foresters immigrated to BC, especially from Europe and the United States, bringing much experience and knowledge. In 1956 about 200 students and 27 faculty of the Sopron Forest Engineering University left Hungary for Austria during an abortive revolution, and after much hardship ended up as the Sopron

Division at UBC. During the 1957-61 period about 140 students, 13 of whom were women, graduated from the Sopron Division. Those that remained in forestry greatly boosted the numbers of foresters in BC and brought a European perspective to forest management.

Another source of RPFs over the years has been from the accreditation of people already experienced and technically trained in forestry work. Amendments to the *Foresters Act* in 1970 made it possible for them to enroll as forestry pupils. It was a tough road as they usually ended up taking at least 20 or more courses in their spare time so that they could qualify for registration. Those that made it generally made highly competent foresters.

The 1970 *Foresters Act* amendments established three classes of members: Professional Foresters (registered), Foresters-in-Training (enrolled) and Forestry Pupils (enrolled). The Act also introduced the title "Registered Professional Forester (RPF)"; deleted "teaching" from the definition of forestry practice; and established a discipline committee.

The 2003 amendments to the Foresters Act saw yet more significant changes. A new category of membership was created – Registered Forest Technologist (RFT). Along with this class of member came the ability for RFTs to practice certain limited aspects of professional forestry as well as implement plans that an RPF has signed off on. In the first year of implementation almost 400 technologists signed up for membership with the ABCFP.

Growth of the ABCFP

ABCFP membership has risen steadily and exponentially. In January 1949, 128 members had registered. By 1951 the number had grown to 174. By 1962, the year of the first Annual General Meeting held in the interior (in Kamloops), the number had more than doubled to 363. Today (2005), there are over 4,400 members with the inclusion of the RFTs.

Issues within the Association

The Association was in search of an identity. Clearly from the beginning it was important to set quality standards for entry and to have an administrative process for dealing with registration. But members continually debated whether the association should be solely a registering body or should become more of an advocacy group. It was not until 1978-79 that the Council was authorized by the members to make public statements without going to a referendum.

Debates also arose about the matter of broadening membership to include technologists, the use of professional title, and the role of the professional *versus* that of the technologist. In the late sixties the Association resolved to have the technologists form their own society. As already mentioned, the issue arose once again and the technologists are now part of the forestry profession.

How to Become a Forester

The *Foresters Act* mandates that only qualified professional individuals who are members of the Association of British Columbia Forest Professionals (the "ABCFP" or the "Association") may practice professional forestry as defined in the Act

(“Professional Forestry”). In return for this privilege, forest professionals are obliged to meet certain stringent academic requirements and must live up to a code of ethics and professional practice standards.

These requirements, as well as the code of conduct, are set and administered by the Association. The Association is in turn charged under the Act with the duty to uphold the public interest in the practice of professional forestry by ensuring the competence, integrity, independence, and accountability of all individuals practicing forestry within BC.

Enrolment as a forest professional

To determine your eligibility for enrolment as a forester-in-training (FIT) or trainee forest technologist (TFT), contact the Association at: Registration Department Association of BC Forest Professionals (phone: 604-687-8027 or e-mail: admissions@abcfp.ca).

Allied science programs

The allied science program is a complement to the FIT and TFT programs and is designed for people with non-accredited forestry degrees or diplomas or other degrees or diplomas the Board of Examiners deems acceptable to allow for enrolment under these categories.

Forestry pupil (FP) program

The FP program is designed for individuals who do not have the requisite university degree but have extensive experience in the forest sector. These are individuals who want to work towards becoming an RPF. Each person is assessed individually by the Board of Examiners and given a list of competencies they need to acquire before writing the registration exam. This program is being phased out. Enrolment will no longer be accepted after November 30, 2005. People already in the program by then will be allowed to complete the program. In the future those who want to gain the competency requirements to become an RPF will be assessed individually but there will be no formal program.

Special permits

The ABCFP may grant limited licenses to non-members to engage in the practice of professional forestry within BC if they demonstrate they have the knowledge to do so. The scope of practice for such individuals is very limited as is the length of time on the permit. The ABCFP is also able to grant special permits to visiting foresters who are registered in other provinces.

As members of the Association of British Columbia Forest Professionals, all limited license and special permit holders are governed by the Act, the Association By-laws (including the Code of Ethics), resolutions of Council, and various policies and procedures of the Association in force from time to time.

Accredited university and college programs

The Canadian Forestry Accreditation Board is responsible for the accreditation of Canadian university forestry baccalaureate programs for the purpose of meeting academic requirements for professional registration. As of 2002, the following schools have accredited programs:

- Lakehead University: Faculty of Forestry
- Université Laval: Faculté de forestières (in French)
- University of Alberta: Faculty of Agriculture, Forestry & Home Economics
- University of British Columbia: Faculty of Forestry
- Université de Moncton: Sciences forestières (in French)
- University of New Brunswick: Faculty of Forestry & Environmental Management
- University of Northern British Columbia: Forestry Program

Ethics and the Professional Forester

The ABCFP has been entrusted by society to protect its interest in the management of forest lands in BC. Under the *Foresters Act* (RSBC, 2003) the Association is charged with governing the conduct of its members and with the maintenance of high professional standards. The *Foresters Act* empowers the Association to prescribe a Code of Ethics (the Code) demanding integrity, competence and fairness.

Forest prefessionals are expected to practice good stewardship of forest lands. A forest is a dynamic ecosystem. Members understand that forest management involves decisions that affect this ecosystem and that forest land and resources must be managed on the basis of sound ecological principles. Such wise management will enable society to use and enjoy the full range of benefits from their forest resources.

The Association fosters good stewardship by maintaining high standards of admission, by advising and supporting its members who uphold this Code, by disciplining members whose professional performance is unsatisfactory, and by commenting, as appropriate, on forest policy and forest land management.

This Code of Ethics and the practise standards are binding on all members of the Association however or wherever they may practice, and each member shall practice their profession accordingly.

The forester and practice standards

Standards of professional practice ("standards") are mandated by the ABCFP's By-laws. These standards are intended to focus on certain general principles, which assist in defining and demonstrating the high levels of forestry professionalism in BC. They do not raise the bar of professional standards beyond the high standards that already exist today.

The word "standard" is common in forestry. It generally describes a baseline for technical aspects of work. Standards of professional practice differ in that they describe measures of professional performance.

These standards are a practical guide for a member's everyday professional practice. They apply to all practice areas regardless of specialization. They deal with professional practice expectations related to competence, independence, integrity, due diligence and stewardship. The standards do not prescribe technical forest management standards.

The standards are, first and foremost, a tool designed to help forest professionals assess their practice relative to the expectations of peers, colleagues and the profession as a whole. The standards are performance baselines against which forest professionals may be measured if their practice is called into question. Each of these standards therefore flows from the *Foresters Act* and ABCFP By-laws, including the Code of Ethics.

Objectives

The objectives for these standards include the provision of:

- Performance benchmarks for daily practice and conduct
- Additional means for the public to know what they can expect from practitioners
- Indicators of quality
- Support for legislated rights to practice and title
- Recognition of the obligations that come with professional practice privileges
- Principles to evaluate ones practice through self-assessment, peer review and individual learning plans

Milestones in the Forestry Profession in BC

Stage 1: Unregulated Exploitation

1908 Chair of Forestry created at the University of New Brunswick.

1908 Canadian Society of Forest Engineers (CSFE) founded, later becomes Canadian Institute of Forestry.

1921 Department of Forestry formed within the UBC Faculty of Applied Science.

1939 Bachelor of Science in Forestry introduced at UBC.

Stage 2: Regulation for Sustained Yield

1947 British Columbia *Foresters Act* permits the registration of foresters, mandates the title, "Registered Forester"; ABCPF founded.

1947 UBC Bachelor of Science in Forestry becomes a four year program following first year forestry or senior matriculation.

1951 UBC Faculty of Forestry formed.

1957 Sopron Division of the Faculty of Forestry established (the last class of Hungarian students graduates in 1961).

1962 The UBC degree program in Forest Engineering suspended.

1964 British Columbia Institute of Technology opens, providing programs in Forestry and Forest Product Technologies.

1967 The HR MacMillan Forestry-Agriculture Building opens at UBC.

1970 British Columbia Professional *Foresters Act* first overhaul of 1947 Act.

Stage 3: Toward an Ecological Approach

1984	Pre-harvesting Silviculture Prescription becomes a policy, requiring RPF sign-off before harvest.
1990	Strategic Plan to address issues affecting the profession passes by large majority of ABCPF members.
1991	Code of Ethics and an Interpretive Guide developed for review by members. At national level a Code of Forestry Practice Standards is developed.
1992	Code of Ethics By-law and updated Strategic Plan approved. Revisions to the *Foresters Act* begin.
1994	Bill 34 – Foresters Amendment Act, 1993 passes; changes were intended to help restore public confidence in the profession.
1995	Record numbers of applications received related to hiring for the Forest Practices Code. Membership reaches 3450 with 2500 registered members.
1996	A judicial review found inadequacies in the pre-1994 version of the *Foresters Act* necessitating a thorough review of current discipline procedures.
2003	Foresters Act amended to include Registered Forest Technologist. The definition is also changed to better reflect the practices forest professionals deal with today. Other changes included a shift towards alternative dispute resolution mechanisms for resolving complaints and the ability to do forest stewardship advocacy. The Act also changed the name of the Association to better reflect the expanded membership.

FOREST SAFETY AND SURVIVAL

by

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FOREST SAFETY AND SURVIVAL

This chapter is intended to provide a general overview of safety issues in the forest environment. It is not within the scope of this chapter to cover first aid techniques. Be aware that a number of emergency situations could arise in the field, including fractures, hypothermia, major chest or head wounds, frostbite, anaphylactic shock, and shock, just to name a few. Topics are discussed briefly, and it is strongly recommended that all forestry workers complete courses in first aid, orienteering, chain-saw use, avalanche awareness, and obtain a firearms acquisition certificate (FAC) and a BC firearms permit if a firearm is being handled.

Before Fieldwork Begins

It is important to take proper precautions before entering the field. This involves equipping yourself with the proper skills and materials required for your type of work, including relevant vaccinations.

What to bring

A comprehensive first-aid kit which includes the following items as recommended by the St. John Ambulance official wilderness first-aid guide (1994):

- 2-6 sterile gauze pads, 10 cm^2
- 1-3 pressure dressings, 17 cm^2
- 1-3 non-adherent dressings, 25 x 40 cm
- 10-20 cleansing wipes (antiseptic)
- 12-24 plastic adhesive strips
- assorted knuckle/fingertip elastic adhesive pads
- 1-3 sanitary napkins, sealed
- 1 roll adhesive tape, 2.5 cm wide
- 3-7 cloth triangular bandages
- 1-2 elastic bandages, 8 cm wide
- approx. 30 mL table salt
- approx. 30 mL baking soda
- 60 mL sugar
- ground to air signal card
- 10-20 cotton tip applicators
- 2 large plastic garbage bags
- tweezers/tick remover
- scissors
- razor and new blades
- antiseptic solution, plastic bottle
- rescue blanket (aluminized
- plastic)
- medicine as required
- instructions for medicines carried
- 2-3 assessment checklists
- 2-3 consciousness records
- oral thermometer (unbreakable case)

Also suggested are the following items:

- water bottle (containing water)
- pocket knife
- flashlight/headlamp
- pocket first aid book
- bear spray
- compass
- emergency food
- watch
- pencil and waterproof field book
- flagging tape
- matches in waterproof container
- mirror

In active logging areas, a hard hat and a high visibility vest must be worn. During hunting season, wear blaze orange headgear and a blaze orange vest or jacket. If there is even a remote chance of getting lost (i.e. >20 m from the vehicle), bring a flare kit and clothing to spend the night.

Action When Lost

- Remain calm.
- Take stock of what you have with you.
- Sit down, relax, then try to figure out where you are.
- Use your compass.
- Proceed to a high point to obtain an idea of lay of the land and to be more readily spotted.
- If you have not discovered your position by at least 1 hr before sunset, admit you are lost.
- If you are lost due to a forced landing, it is important to stay where you are. Remember that search and rescue organizations have planes, highly trained personnel and every kind of equipment and medical supplies ready to find and rescue you.

Prepare to spend the night out:

- Check instructions in flare kit (dusk and dawn are the best times for spotting flares. Pick an opening from a hilltop if possible and aim in front of the approaching aircraft).
- Prepare smoke signal fire – lay out ground to air signals if necessary.
- Make shelter, build a fire.
- Keep busy to prevent exhaustion and exposure.
- Conserve food.
- Find edible plants, fish, and/or game.

Edible plants

Many local plants may be used to supplement the emergency rations in the survival kit but they are usually only palatable in the spring and summer months. The following list includes a few of the most common:

Name	Edible parts	Preparation	Season
Bitterroot	Thick roots	Peeled and boiled	May
Bracken	Young shoots & roots	Shoots boiled, roots roasted	Apr.-Aug.
Fireweed	Stem centres	Split stalk & eat raw	Jun.-Aug.
Mahonia	Blue berries	Raw after first frosts	Sep.-Nov.
Miner's lettuce	Leaves & stems	Raw in salads	Apr.-May
Stinging nettle	Young leaves	Boiled	Apr.-Jul.
Salmonberry	Young stem shoots	Raw	Apr.-May
Spring sunflower	Root or seeds	Roots boiled, seeds raw	May
Thimbleberry	Young stem shoots	Raw	Apr.-May
Violets	Leaves	Raw in salads	May-Sep.
Wild roses	Outer part of fruit or hips	Raw	Sep.-Dec.
Wild tiger lily	Bulb	Boiled	May-Jul.

The young shoots of spruce and tamarack, the inner bark of pine, spruce, hemlock and cottonwood, the buds of poplar, maple, and wild rose are all a source of nourishment in an emergency.

Basic first aid

Remember: deal with priorities first. If the circumstances dictate, rescue the person first. The ABCs of first-aid are:

- Airways
- Breathing – give mouth-to-mouth if needed
- Circulation – stop any bleeding

Artificial (mouth-to-mouth) resuscitation

1. Place the victim on back and clear the mouth and throat.
2. Open the airway by lifting the neck and tilting the head back.
3. Pinch nostrils with your thumb and forefinger and, at the same time, keep pressure on the forehead with the base of the hand in order to keep the air passage open.
4. Place your mouth tightly around mouth and initially blow four full breaths. Watch for chest expansion out of the comer of your eye.
5. Remove your mouth to allow the lungs to deflate.
6. Repeat steps 3 to 5 with one breath every five seconds.
7. DON'T GIVE UP.

Bleeding

1. Apply direct pressure to the wound with a field dressing, other available clean material or your hand if necessary.
2. Do not remove a dressing if saturated, but apply another dressing on top of it and tie tighter.
3. If possible, elevate the wounded area above the heart.
4. Do not remove an imbedded object, but apply pressure around it with a ring pad, and treat as above.

Burns

1. Soak in cold water to relieve pain (30 minutes).
2. Cover with a piece of sterile gauze and bandage firmly.
3. Do not apply greasy substances or ointments to the burn.

Fractures (broken bones)

1. Splint the joints above and below the fracture with available stiff materials (e.g. saplings, tally sack, other parts of body, etc.).
2. Splint deformed fractures in the position found. If the fracture punctures the skin, a skilled first aid attendant may apply traction and straighten the deformity.
3. With open fractures, place a ring (donut) pad around the protruding bone and cover with clean dressing before splinting.
4. Check distal pulses frequently to ensure that circulation is not interrupted.
5. Apply cold compresses to decrease pain and swelling.

Heat exhaustion

1. Have the patient lie down in cool place.
2. Loosen tight clothing.

3. Raise the legs slightly.
4. If conscious, give victim a warm drink.
5. Put the patient in the 3/4-prone position.

Hypothermia

Immediate and positive treatment is required:

1. Get the victim out of the cold, wind and rain.
2. If possible, strip off all wet clothes, get the victim into dry clothes and into a warm sleeping bag; well-wrapped warm rocks placed near the victim will help (i.e., warm rocks from a nearby fire). If possible, strip all clothes from the victim and put him/her into a sleeping bag with another person (also stripped). This skin-to-skin contact is the most effective treatment.
3. If victim is conscious, give warm drinks (non-alcoholic).
4. If victim is semi-conscious or worse, try to keep them awake and give warm drinks.

Frostbite

Superficial frostbite is characterized by a numbness and white or waxy skin. Warm the part with body heat by placing it against a bare stomach or in the armpit. Hold a warm hand over nose, ears, or cheeks. Remember, "when your feet are cold, put on a hat".

Deep frostbite is more serious. The affected area has a hard and woody feeling. Do not try to re-warm deep frostbite outside or by exercising the affected part. The victim should be moved inside as soon as possible, preferably to a hospital. Thaw the frozen tissue in warm water (42–44°C, no hotter) for 20–30 min. (very painful). Do not use cool or cold water. Do not walk on thawed feet or toes as serious damage may result. Never rub frozen tissue with snow, and do not massage before, during, or after re-warming.

Unconsciousness

Unconsciousness means that a person fails to react to voice or touch. Whatever the degree of unconsciousness, the victim is in extreme danger and has no self protection from choking on blood, vomit or the tongue. Before seeking help, place victim in the drainage position. Gently turn on side, injured side down, with cheek on the ground. Keep chin off the chest, make sure that the victim's mouth is open and the airway straight and clear.

Leaving injured person in the bush

If you must leave your partner in the bush:

A. Make sure victim is comfortable and treat all injuries before you leave. If there is a danger of victim becoming unconscious, put victim into the drainage position.

B. Leave victim with:
    1. Shelter
    2. Food and water
    3. Fire, wood, kindling, matches
    4. Knife, axe
    5. Flare kit

6. Extra clothing, both over and under
7. Watch

C. Tell victim of your plans:
    1. Direction and route you are taking.
    2. Estimated time of return.
    3. What you will do when you reach camp or the vehicle.
    4. Reassure victim before you leave.

D. Mark the location of the victim well with flagging tape; you may have to return in the dark.

E. Flag or blaze your way out, using your compass.

F. Take air photos with you, having marked your partner's location before leaving.

Wilderness Health Risks

Diseases

Field workers can come into contact with a variety of diseases. Most are extremely rare, and we include only the most dangerous or most common in BC.

Hantavirus

Hantavirus is a very rare disease which has caused death in over 60% of the diagnosed cases in North America. The virus has caused three deaths to date in BC. Two of these where from cleaning mouse-infested areas and breathing the virus in on dust. The third person was a small mammal trapper, believed to have caught the virus through fieldwork.

Symptoms:

Symptoms of Hantavirus Pulmonary Syndrome are initially very similar to the flu. In early stages, a person may have a fever, sore muscles, headache, feel sick to their stomach, vomit, and have shortness of breath. Within about 12 hours of experiencing these initial symptoms, fluid will build up in the lungs and 48 hrs later, the patient will die. Early diagnosis is therefore crucial. If a worker develops these symptoms, seek medical attention immediately and advise the nurse of the occupational risk of Hantavirus as this will considerably speed-up admission into emergency.

Preventative measures:

For persons whose occupations involve frequent rodent contact (e.g. mouse-trappers), a baseline serum sample should be drawn at a local lab. You must first get a doctor's prescription to get the test done, and you should then be able to make arrangements with a lab to take the samples and then store them for a specified amount of time. Keep something in your wallet which notes at what lab your serum sample is kept. If you become ill, speedy diagnosis is important; this is done by comparing a blood sample with your baseline sample, and the hospital you end up at will need to know where this baseline sample is.

When handling rodents or handling and cleaning rodent traps, workers should wear a half-face air-purifying (or negative pressure) respirator or PAPR equipped with HEPA filters. Respirators are not considered protective if they are not the right size or if facial hair interferes with the face seal. Make sure your respirator fits properly and seals by lighting a cigarette near the fitted mask and seeing if you can smell it. Other types of masks (such as paper masks) and other filters WILL NOT WORK, so ensure you purchase the right kind.

Workers should wear rubber or latex gloves when handling rodents, or when handling and cleaning rodent traps. Latex gloves should be discarded after each use. Workers should wear coveralls. Coveralls and trapping gloves should be kept in a sealed bag between uses. If dirty traps are transported between sites in a vehicle, they should be placed in sealed bags for the ride. Disinfect traps and clothing with a commercial disinfectant or bleach solution. Traps should be soaked for several hours and scrubbed in the solution.

Giardia

This is an intestinal infection caused by a parasite carried by wild animals. Symptoms include diarrhoea, abdominal cramps, nausea and vomiting, weight loss, and fatigue. The infection can last from 1 to 3 weeks or longer. The disease is not considered life-threatening, but can be very uncomfortable.

The *Giardia lamblia* parasite is quite common in western Canadian water bodies, even in very isolated areas. Water from lakes and streams should always be boiled for at least two minutes or chemically treated with special kits available from wilderness travel stores. Alternatively, you can put 4 drops of household chlorine bleach in one gallon of water (about two 2L pop bottles worth), stir and let sit for 30 minutes. Be careful with this or your stomach lining may suffer. Giardia is not as common in eastern Canada.

Lyme disease

Lyme disease is caused by the bacterium *Borrelia burgdorferi* (Bb) which is carried by ticks and can be transferred to humans when bitten by the tick. Lyme disease has been found in ticks from all Lower Mainland areas, and heavily infected areas include the Sunshine Coast and Vancouver island. The western black-legged tick likes to inhabit low vegetation along forest trails and rock exposures along the coast and is most active between January and March. Ticks also cause relapsing fever, tularaemia, and Rocky Mountain Spotted Fever. Not all ticks carry the Lyme bacteria and a bite does not always result in Lyme disease.

If you are working in areas where ticks are common in the vegetation, take the following precautions: wear light-coloured clothing; tuck your pants into your boots or socks and tuck your top into your pants; if the vegetation is high, wear a wide-brimmed hat; check your body, scalp, and bedding for ticks every evening; and regularly check pets which go into the area.

If you find a fastened tick, it will have to be removed carefully, as the tick burrows into the skin and can leave behind its mouthparts when pulled away suddenly. Use tweezers or a tick-remover to gently get a hold of the tick as close to the skin as possible. Without squeezing the tick, gently lift it straight out. Clean the bite area with rubbing alcohol or soap and water. Also, keep the tick in an airtight container. In case you develop symptoms of Lyme disease, the tick can be easily tested.

Symptoms can appear days or weeks after being bitten. General symptoms of headache, muscle and joint pains, fatigue and weakness of the facial muscles occur. A skin rash, especially one that looks like a "Bull's Eye" may appear. If you have removed a tick and you experience these symptoms, your doctor will prescribe antibiotics that kill both Lyme disease and Rocky Mountain Spotted Fever.

Lyme disease is not a rapidly progressing disease, but it is serious. The worst complications of Lyme disease can be avoided if it is caught early.

Rabies

Rabies is a viral disease transmitted by animal saliva. This disease affects the nervous system, causing increased difficulty in swallowing, excessive drooling, muscle spasm or weakness, and strange behaviour. If not treated in time, rabies kills almost all of its victims. BC has had no recent cases of human rabies, although almost 50 people per year are treated for suspected exposure. The most common rabies carriers in BC are bats. It is crucial to begin treatment for suspected rabies as soon as possible. Rabies typically takes two to four weeks to display symptoms. If you intend to work on bats, or with other animals that are likely to carry rabies (skunks, wolves, and racoons), you can take a series of rabies vaccination shots.

Insects

Field workers come into contact with a variety of insects. We identify the most common in our descriptions below.

Biting flies

Blood feeding flies such as blackflies, mosquitoes, horseflies, and deerflies are hard to avoid during the summer months. Although these flies are not associated with the transmission of any significant human diseases in BC, they are associated with biting habits causing pain and irritation to their human hosts.

Blackflies bite by day and do not commonly enter indoors. The bite of the blackfly is not usually felt immediately. However, the resultant swelling and itching is usually severe and persistent. The reaction may involve a condition known as "blackfly fever" which is manifest as a headache, fever and nausea. Repellents can provide some protection from blackfies. For protective clothing to be effective it must be tight fitting, particularly at the collar and cuffs.

Mosquitoes are more active by night and will readily enter indoors. As with blackflies, light coloured clothing is the least attractive, but where as blackflies are deterred by tight fitting clothing, mosquitoes are less likely to bite through loose fitting garments. Repellents may turn the mosquito away before it lands, but will not drive the flies more than a metre or two off.

Horeseflies and **deerflies** are persistent in attack and vicious biters. They lurk on the edge of forest openings and are most active on clear days. Each female only feeds every 2-3 days once it has obtained a full blood meal, but it may take several bites to reach this state. Adequate methods of protection are lacking. Once feeding has begun it is often difficult to dislodge the fly from the skin, and it will persist in attack even after it has been displaced. An attacking fly takes a few seconds to get settled before it bites, during which time a strong hand is often the best deterrent.

Wasps and bees

Although bees possess a powerful sting they will rarely use it unless the hive is approached too closely, or they get trapped in clothing. Unlike other bees and wasps, the honeybee stinger can only be used once and possesses a tiny barb which holds it and the insect in the wound. If an attacking honeybee is brushed off with the hand, the remaining poison sack can be removed by the stroke of a knife quickly and firmly along the surface of the skin lifting the stinger out. Social wasps (yellow-jackets and hornets) attack in groups to defend their nests, but unlike honeybees, they can sting repeatedly without dying.

Bee and wasp venoms contain various enzymes and histamine which is responsible for the localized swelling and smarting around the site of a sting. Stings are very painful but are not dangerous unless a person is stung repeatedly or is allergic. A sting can be treated with vinegar, lemon juice or a mixture of meat tenderizer and saliva for some degree of relief. A severe allergic reaction is marked by reactions distant from the sting site, breathing may become laboured, confusion and weakness will follow. Symptoms can progress from mild to severe in 5-15 minutes. Individuals with known allergies to bees or wasps MUST carry an epinephrine (adrenalin) kit and should always discuss their allergy with co-workers.

Spiders

The black widow spider is common on Southern Vancouver Island and in the interior of the province. It is usually found away from occupied buildings, in fields, beneath logs or in disused outbuildings. The bite itself is not usually felt, but is marked by two red spots. The pain that develops throughout the body peaks after 2-3 hours, but will persist for almost two days. Ice applied to the bite site will delay absorption of the poison, giving the body more time to neutralize the toxin. The degree of reaction to a black widow bite depends on the amount of venom injected, the age and health of the victim, the part of the body attacked and the treatment applied. Mortality is rare, and most victims recover without needing medical attention.

Some common ailments

The proceeding information was obtained through the BC Ministry of Health, Vancouver/ Richmond Health Board "From the Health Files" datasheet series (British Columbia, 2002). The following ailments may be common to persons working in isolation.

Salmonella poisoning

Field camps often do not have any refrigeration. Salmonella poisoning can result from allowing foods to spoil, especially eggs, fish, or meats. Symptoms include rapid onset of abdominal pain, diarrhoea, nausea, fever and vomiting. Dehydration may be severe.

Blood poisoning

Blood poisoning and gangrene can result from allowing a bad blister to go untreated. Symptoms that your blister may have passed the trivial stage are: redness, swelling and hot feeling in a large area surrounding the blister; blue lines travelling "upvein" from the blister; pain and aching in the groin area. At this point antibiotics are advisable. To prevent a blister from getting to this stage, bathe it in very hot, heavily salted water several times throughout the day.

Tetanus

If you puncture your skin deeply, in such a manner that the wound heals over on the surface, the anaerobic conditions necessary for tetanus to develop may occur. If you have not had a tetanus shot within the last 10 years, be sure to clean the wound thoroughly before it closes up, and watch for symptoms of tetanus. This may include muscles spasms and severely progressing tightness and swelling of neck muscles.

Sunburn

Severe sunburn may occur even in the late winter months. Wear a hat and make the best use of shade.

Wildlife

Bears

BC has two bear species, the black bear (*Ursus americanus*) and the grizzly or brown bear (*Ursus arctos*). Grizzly bears are responsible for a greater number of serious injuries and deaths in BC, despite being 1/10th as abundant as black bears. However, both species should be treated with extreme caution.

The black bear may vary in colour from black to cinnamon brown. These bears are usually not aggressive, but do engage in predatory attacks. Always try and fight off an attacking black bear, and do not "play dead".

Grizzlies occasionally make unprovoked attacks, but most attacks result from being surprised at close quarters. Grizzlies have a defined shoulder-hump and dished-shaped faces. They are usually brownish or yellowish-brown, but vary in colour from blond to black. It is recommended that one "play dead" if approached by a grizzly bear. Lie on your stomach and cover your neck, and keep your pack on, as it can offer some protection. If a grizzly bear is stalking in an apparent predatory situation, do not play dead and try to appear as large as possible.

The best way to avoid bear-human conflict is to give bears advance warning of your approach. Try to stay in open areas where you can be easily seen and heard. While walking through thick bush, stay alert and make an extra effort to be noisy, especially near loud streams and falls. Learn to recognize bear signs such as overturned logs, patches of earth overturned in search for roots, dug up mammal burrows, broken tree branches, slashes on tree trunks, bear scat or tracks. Berry patches, riverbeds, and valleys are hotspots for bears, as they feed on vegetation in these areas. Also avoid areas where ravens are numerous as this is an indication of a nearby carcass, and one must never get close to a female with cubs. Always avoid carrying odours that may attract bears. Never cook or store food near a tent or sleeping area. For further information regarding bear-human encounters, Steve Herrero's book (1985) entitled "Bear attacks: their causes and avoidance" is recommended.

Other potentially dangerous animals

Cougars have been known to attack humans. Vancouver Island has particularly high cougar densities and thus, proper care should be taken. Look up on bluffs and behind you, and keep an eye out for tracks. Like the black bear, one should always fight off a cougar with all available means.

Cow **moose** accompanied by young calves and bull moose during the rut may be aggressive. Climbing a tree may be the best means of escape.

It is advisable to carry a snake-bite-kit if working in **rattlesnake** habitats. Research the merits of various snake-bite-kits before selecting one.

Vehicle Maintenance, Troubleshooting, Off-road Truck Use and Radio Use

Radio calling

Field workers often find themselves travelling or working in areas where there is active logging. Forest companies and other officials communicate by two-way radio in actively logged areas in order to operate safely. This is very important because, on many roads, one-way travel is required for loaded logging trucks because of their size and speed. By convention, loaded trucks travelling out from a work site have the right-of-way and will announce their locations by radio. Others travelling in on the same road should pull off until the loaded truck passes.

Most logging roads are named and signs tend to be posted at intersections, along with the radio frequency in use. Kilometre markings are also posted, generally on diamond-shaped signs nailed to trees near the road. By convention, kms increase as one leaves the highway and approaches a work site. Also, there are conventions for radio calling of which you need to be aware.

Always announce when you first enter a road, and identify what you are driving. Then as you travel, announce your location at least every other km. If kms are increasing, announce that you are “empty”, if they are decreasing, you are “loaded”. For example, if you are in a blue pickup, and you just passed the 25 km marking on Red Creek road heading away from the highway, you would announce: “blue pickup empty at 25 km Red Creek road.” If you hear someone announce that they are a “loaded” truck on Red Creek at 26 km, assume it is a loaded logging truck, find a place to pull off, announce that you did so, and wait until the vehicle has passed.

One must receive permission from the MoF or the licensee to use a radio frequency. The Forest District Office for the area in which you are working will have information regarding logging activities and radio frequencies. It is not mandatory to communicate by radio on public crown lands, but it is advisable to enquire at the Forest District Office if the road is being used enough to warrant a radio. It should be noted that it is unlawful to use profane language at any time and it is not good practice to criticize or debase anyone’s character over the radio.

Vehicle operation, maintenance and troubleshooting

Simple maintenance rules of all vehicles

It is important not to run out of engine oil. If there is not enough water in the radiator, or if the radiator is not cooling the engine down (perhaps due to a leak), and the engine is overheating, do not drive it. Components may warp, crack or be otherwise damaged, and the engine may seize.

Simple rules for parking trucks

Leave parked vehicles with manual transmission in first gear, with the emergency brake on. Never leave a vehicle in neutral. For vehicles with automatic transmission, always shift into PARK, and apply the emergency brake. Large trucks may roll when parked on a hill, so park with the wheels angled into the curb on a downward hill and with wheels angled out from the curb on upwards hills.

Flat tire

If you are on gravel roads, you can drive a fair distance on a partly flat tire. Do not drive on the highway with a partly flat tire because if it breaks, you could swerve into oncoming traffic. If the tire is totally flat, driving on it will bend the wheel rim which is very expensive to replace.

To change a tire

Make sure the truck is not in neutral and place rocks or wood blocks in front or behind the tires so that the truck does not roll once it is jacked up. Crack (loosen) the bolts of the flat tire while it is still on the ground. Do not take the bolts off entirely as the truck could fall over. Place a jack under the wheel axle, in such a position that it looks least likely to fall over once the truck is jacked up. Jack the vehicle up until the tire is just off of the ground. Remove the tire and replace it with a new one. When retightening the bolts, tighten them in a balanced fashion. First one, then the bolt across from it, etc. When the bolts are all tightened down, jack down the truck. After you have driven for 15 minutes down the road, get out and check that the bolts are stiff-tight. If the wheel was put on slightly askew, the bolts will loosen and the wheel will roll off. Repair your flat tire right away.

Push-starting and jump-starting

A common field problem is leaving the lights on, making the battery go dead. If you have a standard vehicle, you can push-start it. If you have an automatic vehicle, you will have to get another vehicle and jumper cables to jump-start it.

Push-starting can be done with only one person. With the ignition ON, push the truck down a hill. If forward, put it in first or second gear, but keep the clutch in so that the vehicle will roll. When the truck gains a fair bit of momentum, let the clutch out and the vehicle should start. Keep the engine running as the battery will need to charge up again.

Jump-starting is accomplished by parking an operating vehicle close to the dead battery and leaving it running. The positive end of the jumper cables is then attached to the positive terminus of the working vehicle's battery, and the negative end to the negative terminus. Do not let the two clips of the other end touch each other. Clip the positive end onto the positive terminus of your dead vehicle, and the negative end to the engine block (a ground). Start your vehicle. Remove the cables by removing the negative cable clip first, then the positive clip from the battery terminal, and keep the vehicle running for at least 20 minutes to recharge the battery.

4 wheel drive

4WD can be used when you encounter a mud-slippery road and your vehicle starts sliding, or to navigate very rough or steep roads. Most importantly, 4WD should be used with speeds of under 50 km/h.

Learn to operate the type of 4WD vehicle that you are using. Some all wheel drive (AWD) vehicles will automatically shift power to the wheels that require them. Others need to be manually shifted into 4WD. Of those, some can be shifted while under power with a gear shift located in the cab, while older models must be stopped and put into neutral. Some older trucks will have manual hubs which must be properly used to avoid expensive repairs. These trucks are put in 4WD by stopping the vehicle, climbing out, and twisting hubs on the front wheel to a "locked" position. To disengage, you need to stop again, and twist the hubs back. Some older models also have to be driven backwards a few metres to disengage 4WD. Always remember to switch back to 2WD when 4WD is no longer necessary.

Aircraft and boats

When possible, speak to pilots in person before approaching their aircraft. Often they will have specific details relating to the safety of their aircraft and will give you a safety briefing.

Helicopters

- Approach and leave a helicopter on the downslope side, to avoid the main rotor. Crouch while approaching and leaving.
- Never walk behind a helicopter on the downslope side. Always approach and leave within the pilot's field of vision, to avoid the tail rotor.
- Near the helicopter, always carry tools horizontally, below waist level, and never upright or on the shoulder.
- Loose items (e.g. parkas, empty cans) should be secured or removed from the helispot. No fires should be made in the helispot area.
- Have the crew and unloaded equipment move to a safe area, in view of the pilot, after unloading. Have them wait in a safe, visible (usually upwind) area from the helispot, when the helicopter approaches for a pick-up.
- Double-check baggage compartment and passenger doors after loading and unloading. Keep seatbelts fastened continuously when in flight, and buckle seatbelts after you exit the helicopter as well.

Fixed-wing aircraft

- When on the ground, stay away from the propeller. When in flight, keep seat-belts fastened continuously.
- With a float plane, it is safest to wear a hard had while loading and unloading, and beware of striking the head or neck on the flat trailing edge of the wing. This hazard may be serious when working on a float plane dock.
- Wheeled aircraft occasionally use roads, gravel bars, and other unprepared strips when transporting field workers. When waiting for a pickup, field crews should check the landing zone to ensure that it is long enough, that

the ground is not too soft, and that boulders are removed. It may be helpful to mark both ends of the strip, and to mark the downwind (approach) end at both sides, where it can be checked by the pilot immediately before touchdown.

- Radio the pilot before landing to exchange instructions.

Boats

Become familiar with the use of the craft that you will be piloting. Emergency supplies in a waterproof container, and a spare oar or paddle should be attached to the boat. Life jackets should be worn at all times. Patch kits should always be carried with inflatables and canoes. It may be prudent to secure inflatables with a long line to shore upstream, while ferrying crew or equipment across fast water.

References

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Merry, W. 1994. St. John Ambulance: The official wilderness first-aid guide. McClelland & Stewart Inc., Toronto. 390 pp.

FORESTRY ORGANIZATIONS AND PUBLICATIONS

by

L. Tolland, M.Sc.,
L. Unwin,
M. Saprunoff
and
J.J. Myers, HND

Forestry Related Organizations and Associations

Association of British Columbia Forest Professionals (ABCFP)
1030 - 1188 West Georgia Street
Vancouver, BC V6E 4A2
Tel: 604.687.8027
E-mail: info@abcfp.ca
www.abcfp.ca/

Association of Professional Engineers and Geoscientists of British Columbia
200-4010 Regent Street
Burnaby, BC, V5C 6N2
Tel: 604.430.8035
E-mail: apeginfo@apeg.bc.ca
www.apeg.bc.ca

BC Wood Specialties Group
Suite 200, 9292, 200th St.
Langley, BC, V1M 3A6
Tel: 604.882.7100
www.bcwood.com/

Building Supply Industry Association of British Columbia
Unit #2, 19299-94th Avenue
Surrey, BC, V4N 4E6
Tel: 604.513.2205
www.bsiabc.ca/

Canadian Forestry Association
185 Sommerset Street, Suite 203
Ottawa, ON, K2P 0J2
Tel: 613.232.1815
E-Mail: cfa@canadianforestry.com
www.canadianforestry.com

Canadian Forest Service
Natural Resources Canada
580 Booth Street, 8th Floor
Ottawa, ON, K1A 0E4
Tel.: 613.947.7341
E-mail: cfs-scf@nrcan.gc.ca
http://cfs.nrcan.gc.ca/

Canadian Institute of Forestry
606-151 Slater Street
Ottawa, ON, K1P 5H3
Tel: 613.234.2242
E-mail: cif@cif-ifc.org
www.cif-ifc.org/

Canadian Lumbermen's Association
27 Goulburn Avenue
Ottawa, ON, K1N 8C7
Tel: 613.233.6205
E-mail: info@cla-ca.ca

Canadian Lumber Standards Accreditation Board
#406 - First Capital Place, 960 Quayside Place
New Westminster, BC, V3M 6G2
Tel: 604.524.2338
Email: nlga@axionet.com

Cariboo Lumber Manufacturers' Association
205-197 N. Second Ave.
Williams Lake, BC, V2G 1Z5
Tel: 250.392.7778
E-mail: clma@wlake.com

Central Interior Logging Association
201-850 River Road
Prince George, BC, V2L 5S8
Tel: 250.562.3368
E-mail: cila@pgonline.com
www.cila.ca/Default.aspx?PageID=d564

Council of Forest Industries
1200-Two Bentall Centre, 555 Burrard Street, PO Box 276
Vancouver, BC, V7X 1S7
Tel: 604.684.0211
E-mail: info@cofi.org
www.cofi.org

Forest Engineering Research Institute of Canada
Western Division
2601 East Mall, The University of British Columbia
Vancouver, BC, V6T 1Z4
Tel: 604.228.1555
www.feric.ca

Forest Products Association of Canada
Suite 410, 99 Bank St.
Ottawa, ON, K1P 6B9
Tel: 613.563.1441
Email: ottawa@fpac.ca
www.fpac.ca

Forintek Canada Corp.
Head Office and Western Division
2665 East Mall, The University of British Columbia
Vancouver, BC, V6T 1Z4
Tel: 604.224.3221
E-mail: info@van.forintek.ca
www.forintek.ca/

Interior Lumber Manufacturers' Association
440 Sealion Place
Nanaimo, BC, V9V 1B3
Tel: 250.860.9663
E-mail: ilma@ilma.com
www.ilma.com

National Lumber Grades Authority
406 - First Capital Place, 960 Quayside Drive
New Westminster, BC, V3M 6G2
Tel: 604.524.2393
Email: info@nlga.org
www.nlga.org

Pacific Forestry Centre
506 West Burnside Road
Victoria, BC, V8Z 1M5
Tel: 250.363.0600
www.pfc.forestry.ca

Pacific Lumber Inspection Bureau
33442 First Way South, Suite 300
Federal Way, WA, USA, 98003
Tel: 253.835.3344
Email: plib@foxinternet.com
www.plib.org/

Society of American Foresters
5400 Grosvenor Lane
Bethesda, MD, 20814-2198
Tel: 301.897.8720
E-mail: safweb@safnet.org
www.safnet.org/index.html

Truck Loggers Association
725-815 West Hastings St.
Vancouver, BC, V6C 1B4
Tel: 604.684.4291
E-mail: office@truckloggers.com
www.truckloggers.com

Canadian Forestry Education

University level

Faculty of Agriculture, Forestry, and Home Economics
2-14 Agriculture - Forestry Centre, University of Alberta
Edmonton, AB, T6G 2P5
Tel: 780.492.4931
www.afhe.ualberta.ca

Faculty of Forestry and Environmental Management
University of New Brunswick
PO Box 44555
Fredericton, NB, E3B 6C2
Tel: 506.453.4501
www.unb.ca/forestry.home.html

Faculté de foresterie et de géomatique
University Laval
Bureau 1151, PQ, G1K 7P4
http://ffg.ulaval.ca

Faculty of Forestry and the Forest Environment
Lakehead University
955 Oliver Road
Thunder Bay, ON, P7B 5E1
Tel: 807.343.8507

Faculty of Forestry
University of Toronto
33 Willcocks Street
Toronto, ON, M5S 3B3
Tel: 416.978.6152
www.forestry.utoronto.ca

Faculty of Forestry
University of British Columbia
Forest Sciences Centre, 2424 Main Mall
Vancouver, BC, V6T 1Z4
Tel: 604.822.2727
www.forestry.ubc.ca

Faculty of Natural Resources and Environmental Studies
University of Northern British Columbia
3333 University Way
Prince George, BC, V2N 4Z9
Tel: 250.960.5555
www.unbc.ca/forestry

Non-university level

Algonquin College
Upper Ottawa Valley Campus
351 Pembroke St. E
Pembroke, ON, K8A 3K2
Tel: 613.735.4700
www.algonquinc.on.ca/acad_menus/current/0108X4FPM.htm

Cégep de Baie-Comeau
537, boul. Blanche
Baie-Comeau, PQ, G5C 2B2
Tel: 418.589.5707
www.cegep-baie-comeau.qc.ca/foresterie/index.htm

Cégep de Chicoutimi
534 Rue Jacques-Cartier Est.
Chicoutimi, PQ, G7H 1Z6
Tel: 418.549.9520
www.cegep-chicoutimi.gc.ca/index.htm

Cégep de la Gaspésie et des Îles
96, Jacques-Cartier Street
Gaspé, PQ, G4X 2S8
Tel: 418.368.2201
www.cgaspesie.qc.ca/english/campus/prog/190_b0ga/index.html

Cégep de Rimouski
Technologie forestiere
60 Rue de l'Évêché Ouest
Rimouski, PQ, G5L 4H6
Tel: 418.723.1880
www.cegep-rimouski.qc.ca/dep/tfor/framdep.htm

Cégep de Rouyn
Technologie forestiere
Campus de Rouyn-Noranda
425 boulevard du College
Rouyn-Noranda, PQ, J9X 5E5
Tel: 819.762.0931
www.cegepat.qc.ca/prog/rn190bo.htm

Cégep de Sainte-Foy
2410 chemin Sainte-Foy
Sainte-Foy, PQ, G1V 1T3
Tel: 418.659.6600
www.cegep-ste-foy.qc.ca

College of New Caledonia
3330-22nd Avenue
Prince George, BC, V2N 1P8
Tel: 250.562.2131
www.cnc.bc.ca/forestry/index.html

College of the North Atlantic
PO Box 822
Corner Brook, NF, A2H 6H6
Tel: 709.637.8530
www.northatlantic.nf.ca/programs

Department of Forest Resources Technology
Malaspina University-College
900 Fifth Street,
Nanaimo, BC, V9R 5S5
Tel: 250.740.6410
www.mala.bc.ca/www/discover/forestry/index.htm

Department of Renewable Resources
Selkirk College
301 Frank Beinder Way, Box 1200
Castlegar, BC, V1N 3J1
Tel: 250.365.7292
www.rrs.selkirk.bc.ca/main.asp

Department of Renewable Resources Technology
British Columbia Institute of Technology
3700 Willingdon Avenue
Burnaby, BC, V5G 3H2
Tel: 604.434.5734
www.renewres.bcit.ca

Ecole de foresterie et de technolgie du bois de Duchesnay
147 Route Duchesnay
Ste-Catherine-de-la-Jacques-Cartier
PQ, G0A 3M0
Tel: 418.875.3467
www.cscapitale.qc.ca/fp/autre_sites/duchesnay.html

Environmental Training Centre
1176 Switzer Drive
Hinton, AB, T7V 1V3
Tel: 780.865.8200
www3.gov.ab.ca/env/resedu/etc/

Forest Management Institute of British Columbia
2665 East Mall
Vancouver, BC, V6T 1Z4
Tel: 604.224.7800
www.fmibc.org/index.shtml

Forest Technology
Northern Alberta Institute of Technology
Main Campus
11762-106 St.
Edmonton, AB, T5G 3H1
Tel: 780.471.8671
www.nait.ab.ca/programs/FOT/

Maritime Forest Ranger School
Hugh John Flemming Forestry Centre
1350 Regent Street
Fredericton, NB, E3C 2G6
Tel: 506.458.0658
www.mfrs.nb.ca

Saskatchewan Institute of Applied Science and Technology
Woodland Campus
1100-15th Street East
PO Box 3003
Prince Albert, SK, S6V 6G1
Tel: 306.953.7000
www.siast.sk.ca/siast

Sault College of Applied Arts & Technology
443 Northern Ave.
Sault Ste. Marie, ON, P6A 5L3
Tel: 705.759.6700
www.saultc.on.ca/Programs/ForestryTech.htm

Sir Sandford Fleming College
School of Environmental and Natural Resource Sciences
Albert Street South,
PO Box 8000,
Lindsay, ON, K9V 5E6
Tel: 705.324.9144
www.flemingc.on.ca/programs/natres/

Provincial Government Forestry Offices

Alberta

Alberta Sustainable Resource Development
Information Centre, Main Floor, 9920 108 Street
Edmonton, Alberta, T5K 2M4
Tel: 780.944.0313
www3.gov.ab.ca/srd

British Columbia

BC Ministry of Forests
PO Box 9529, Stn Prov. Govt.
Victoria, BC, V8W 9C3
Tel: 250.387.6121
www.gov.bc.ca/for

Manitoba

Manitoba Conservation
Forestry Branch, 200 Saulteaux Crescent
Winnipeg, MB, R3J 3W3
Tel: 204.945.7989
www.gov.mb.ca/natres/forestry

Newfoundland

Forest Resources Headquarters
Fortis Building, PO Box 2006
Corner Brook, NFLD, A2H 6J8
Tel: 709.637.2349
www.gov.nl.ca/forestry

Nunavut

Department of Resources, Wildlife, and Economic Development
PO Box 7, 2nd Floor, McDougal Road
Fort Smith, NT, X1A 2L9
Tel: 867.872.7700
www.gov.nt.ca/RWED/fm

Nova Scotia

Forestry Division
PO Box 68, Truro, NS, B2N 5B8
Tel: 902.893.5671
www.gov.ns.ca/natr

Ontario

Forest Management Branch
Roberta Bondar Place, Suite 400
70 Foster Drive, Sault Ste. Marie, ON, P6A 6V5
Tel: 705.945.6661
www.mnr.gov.on.ca/MNR

Quebec
Ministry of Natural Resources
5700, 4E Western Avenue
Charlesbourg, PQ, G1H 6H1
Tel: 418.627.8600
www.mrn.gouv.qc.ca/english/forest/index.jsp

Saskatchewan
Environment and Resource Development
3211 Albert Street
Regina, SK, S4S 5W6
Tel: 306.787.2700
www.se.gov.sk.ca/forests

Yukon
Resource Development, Department of Economic Development
PO Box 2703, 400-211 Main Street, Shoppers Plaza
Whitehorse, YK, Y1A 2C6
Tel: 867.667.3432
www.emr.gov.yk.ca/Forestry/

Regional Research Centres

Forest Pest Management Institute
Forestry Centre
PO Box 490
Sault Ste. Marie, ON, P6A 5M7
Tel: 705.949.9461
www.utoronto.ca/forest/eso/forcan.htm

Great Lakes Forest Research Centre
1219 Queen Street East
PO Box 490,Sault Ste. Marie, ON, P6A 5M7
Tel: 705.759.5740
www.glfc.cfs.nrcan.gc.ca

Laurentian Forest Research Centre
1055 du P.E.P.S
PO Box 3800
Saint-Foy, PQ, G1V 4C7
Tel: 418.648.3335
www.cfl.forestry.ca

Maritimes Forest Research Centre
Atlantic Forestry Centre
PO Box 4000, Regent Street
Fredericton, NB, E3B 5P7
Tel: 506.452.3500
www.atl.cfs.nrcan.gc.ca/

Northern Forest Research Centre
5320-122 Street
Edmonton, AB, T6H 3S5
Tel: 780.435.7210
www.nofc.forestry.ca/

Pacific Forest Research Centre
Natural Resources Canada
506 West Burnside Road
Victoria, BC, V8Z 1M5
Tel: 250.363.0600
www.pfc.forestry.ca/

Petawawa National Forestry Institute
Forestry Centre
Chalk River, ON, K0J 1J0
Tel: 613.589.2880
www.utoronto.ca/forest/eso/forcan.htm

Pulp and Paper Research Institute of Canada
3800 Westbrook Mall, The University of British Columbia
Vancouver, BC, V6S 2L9
Tel: 604.222.3200
www.paprican.ca

Forest Industry Directories

Madison's Canadian Lumber Directory
PO Box 2486
Vancouver, BC, V6B 3W7
Tel: 604.984.6838

Forest and Forest Industry Periodicals

Canadian Forest Industries
90 Morgan, Unit 14
Baie d'Urfe, PQ, H9X 3AB
Tel: 514.457.2211
www.forestcommunications.com

Canadian Journal of Forest Research
National Research Council of Canada
Ottawa, ON, K1A 0R6
Tel: 613.993.0362
www.nrc.ca

Logging and Sawmilling Journal
PO Box 86670, 211 East 1st Street
North Vancouver, BC, V7L 4L2
Tel: 604.990.9970
www.forestnet.com

Madison's Canadian Lumber Reporter
PO Box 2486
Vancouver, BC, V6B 3W7
Tel: 604.984.6838
www.madisonsreport.com

The Forestry Chronicle
Suite 606, 151 Slater Street
Ottawa, ON, K1P 5H3
Tel: 613.234.2242
www.cif-ifc.org

Truck Logger
Truck Loggers Association
756-815 West Hastings Street
Vancouver, BC, V6C 1B4
Tel: 604.684.4291
www.truckloggers.com

CONVERSION FACTORS

Area

English

1 square link	=	0.435,6 square feet
	=	62.726,4 square inches
1 square foot	=	144 square inches
1 square yard	=	9 square feet
	=	1,296 square inches
1 mil-acre	=	4.84 square yards
	=	100 square links
1 square chain	=	16 square rods
	=	484 square yards
	=	10,000 square links
1 rood	=	40 square rods
1 acre	=	4 roods = 10 square chains
	=	160 square rods
1 acre	=	4,840 square yards
	=	43,560 square feet
	=	100,000 square links
1 square mile	=	640 acres
	=	3,097,600 square yards
	=	27,878,400 square feet

Metric

1 square centimetre	=	100 square millimetres
1 square metre (centiare)	=	10,000 square centimetres
1 square decametre (are)	=	100 square metres
1 hectare	=	100 ares (a)
	=	10,000 square metres
1 square kilometre	=	100 hectares (ha)
	=	1,000,000 square metres

Conversions

Basic relationships:

1 inch	=	2.54 centimetres (exactly)
1 square inch	=	6.451,6 square centimetres (exactly)
1 square centimetre	=	0.155,000,3 square inches
1 square link	=	404.685,642,24 square centimetres (exactly)
1 square centimetre	=	0.002,471,054 square links
1 square foot	=	0.092,903,04 square metres (exactly)
1 square metre	=	10.763,910 square feet
1 square yard	=	0.836,127,36 square metres (exactly)
1 square metre	=	1.195,990 square yards
1 mil-acre	=	4.04,856,422,4 square metres (exactly)
1 square metre	=	0.247,105,4 mil-acres
1 square metre	=	0.039,536,86 square rods
1 square chain	=	404.685,642,24 square metres (exactly)

1 square metre	=	0.002,472,054 square chains
1 acre	=	0.404,685,642,24 hectares (exactly)
1 hectare	=	2.471,054 acres
1 square mile	=	2.589,988,110,336 square kilometres (exactly)
1 square kilometre	=	0.386,102,2 square miles

Circular Plots

1.0 acre	=	117.8 ft radius
0.5 acre	=	83.3 ft radius
0.25 acre	=	58.9 ft radius
0.20 acre	=	52.7 ft radius
0.1 acre	=	37.2 ft radius

Globes and Circles

diameter of circle	=	circumference × 0.318,31
circumference of circle	=	diameter × 3.141,6
area of circle	=	square of Diameter × 0.785,4
surface of sphere	=	square of Diameter × 3.141,6
side of equal sphere	=	diameter × 0.886,2
volume of sphere	=	cube of Diameter × 0.523,6

Length

English

1 inch	=	1,000 mils
1 Gunter's or surveyor's link	=	0.66 feet = 7.92 inches
1 foot	=	12 inches
1 yard	=	3 feet (ft)
1 fathom	=	6 feet
1 chain	=	4 rods = 22 yards = 100 links
1 furlong	=	10 chains = 22 yards
1 mile	=	8 furlongs = 1,760 yards
	=	5,280 feet
1 international nautical mile	=	1.150,779,45 miles
	=	6,076.115,49

Metric

1 millimicron	=	10 ångstroms (Å)
1 micron	=	1,000 millimicrons (mμ)
1 millimetre	=	1,000 microns (μ)
1 centimetre	=	10 millimetres (mm)
1 metre	=	10 decimetres (dm)
1 decametre	=	10 metres (m)
1 hectometre	=	10 decametres (dam)
1 kilometre	=	10 hectometres (hm)
	=	1,000 metres
1 myriametre (man)	=	10 kilometres (km)

Conversions

Basic relationships:

1 inch	=	2.54 centimetres (exactly)
1 international nautical mile	=	1.852 kilometres (exactly)
1 centimetre	=	0.393,700,8 inches
1 link	=	20.116,8 centimetres
1 centimetre	=	0.049,709,70 links
1 foot	=	30.48 centimetres (exactly)
1 metre	=	3.280,840 feet
1 yard	=	0.914,4 metres (exactly)
1 metre	=	1.093,613 yards
1 fathom	=	1.828,8 metres (exactly)
1 metre	=	0.546, 806,6 fathoms
1 metre	=	0.198,838,8 rods, poles, or perches
1 chain	=	20.116,8 metres (exactly)
1 metre	=	0.049,709,70 chains
1 furlong	=	201.168 metres (exactly)
1 metre	=	0.004,970,970 furlongs
1 mile	=	1.609,344 kilometres (exactly)
1 kilometre	=	0.621,371,2 miles
1 international nautical mile	=	1.852 kilometres (exactly)
1 kilometre	=	0.539,956,8 nautical miles

Mechanical-Electrical Equivalents

Power

1 horsepower (hp)	=	550 foot-pounds (ft-lb) per second (sec.)
	=	33,000 ft-lb per minute (min.)
	=	1,980,000 ft-lbs per hour (hr.)
	=	0.275 ft-tons per sec.
	=	16.5 ft-tons per min.
	=	990 ft-tons per hr.
1 horsepower-second (hp-sec.)	=	550 ft-lb
1 horsepower-minute (hp-min.)	=	33,000 ft-lb
1 horsepower-hour (hp-hr.)	=	1,980,000 ft-lb
1 horsepower (hp)	=	746 watts (w)

Energy

1 horsepower-hour	=	2545 BTU
	=	746 KW-hr
1 Kilowatt-hour	=	3418 BTU

Pressure

1 lb per sq in.	=	2.0360” of mercury at 32°F
	=	27.71” of water at 32°F
	=	2.3071 ft of water at 60°F
	=	144 lb per sq ft.
1 in. of mercury	=	491 lb per sq in.
1 in. of water	=	5.2 lb per sq ft
	=	0.0361 PSI

Proportion: Area Basis

Numbers

1 per square inch	=	0.155,000,3 per square centimetre
1 per square centimetre	=	6.451,6 per square inch (exactly)
1 per square foot	=	10.763,91 per square metre
1 per square metre	=	0.092, 903,04 per square foot (exactly)
1 per square yard	=	1.195,990 per square metre
1 per square metre	=	0.836,127,36 per square yard (exactly)
1 per mil-acre	=	0.247,105,4 per square metre
1 per square metre	=	4.046,856,422,4 per mil-acre (exactly)
1 per acre	=	2.471,054 per hectare
1 per hectare	=	0.404,685,642,24 per acre (exactly)
1 per square mile	=	0.386,102,2 per square kilometre
1 per square kilometre	=	2.589,988,110,336 per square mile (exactly)

Area

1 square foot per acre	=	0.229,568,4 square metres per hectare
1 square metre per hectare	=	4.356,000 square feet per acre

Solid Cubic Measure

1 cubic foot per acre	=	0.069,972,45 cubic metres per hectare
1 cubic metre per hectare	=	14.291,34 cubic feet per acre
1 cubic yard per acre	=	1.889,256 cubic metres per hectare
1 cubic metre per hectare	=	0.529,308,8 cubic yards per acre

Special Timber Measures

1 square foot per acre	=	0.229,568,4 square metres per hectare
1 square metre per hectare	=	4.356,000 square feet per acre
1 cubic foot per acre	=	0.069,972,45 cubic metres per hectare
1 cubic metre per hectare	=	14.291,34 cubic feet per acre
1 Hoppus cubic foot per acre	=	0.089,091,70 metres per hectare
1 cubic metre per hectare	=	11.224,39 Hoppus cubic feet per acre
1 cunit per acre	=	6.997, 245 solid cubic metres per hectare
1 solid cubic metre per hectare	=	0.142,913,4 cunits per acre
1 cord[a] per acre	=	8.956,474 cubic metres[a] per hectare
1 cubic metre[a] per hectare	=	0.111,651,1 cords[a] per acre
1 Petrograd standard per acre	=	11.545,45 cubic metres per hectare
1 cubic metre per hectare	=	0.086,614,17 Petrograd standards per acre
1 fathom[a] per acre	=	15.114,05 cubic metres[a] per acre
1 cubic metre[a] per hectare	=	0.066,163,60 fathoms[a] per acre

[a] overall measures of stacked or piled roundwood

Volume

1 millilitre per square yard	=	1.195,990 millilitres per square metre
1 millilitre per square metre	=	0.836,127,36 millilitres per square yard (exactly)
1 millilitre per square yard	=	1.064,681 Imperial gallons per acre
1 Imperial gallon per acre	=	0.939,248,9 millilitres per square yard

1 millilitre per square yard	= 1.278,628 U.S. gallons per acre
1 U.S. gallon per acre	= 0.782,088,80 millilitres per square metre
1 Imperial fluid ounce per square yard	= 33.980,80 millilitres per square metre
1 millilitre per square metre	= 0.029,428,38 Imperial fluid ounces per square yard
1 U.S. fluid ounce per square yard	= 35.368,66 millilitres per square metre
1 millilitre per square metre	= 0.028,273,62 U.S. fluid ounces per square yard
1 Imperial gallon per square yard	= 5.436,928 litres per square metre
1 litre per square metre	= 0.183,927,4 Imperial gallons per square yard
1 U.S. gallon per square yard	= 4.527,188 litres per square metre
1 litre per square metre	= 0.220,887,7 U.S. gallons per square yard
1 Imperial gallon per acre	= 11.233,32 litres per hectare
1 litre per hectare	= 0.089,020,85 Imperial gallons per acre
1 U.S. gallon per acre	= 9.353,695 litres per hectare
1 litre per hectare	= 0.106,909,6 U.S. gallons per acre
1 inch of rain	= 4,671,755 Imperial gallons per square yard
	= 22,611.30 Imperial gallons per acre
	= 5.610,390 U.S. gallons per square yard
	= 27.154,29 U.S. gallons per acre
1 millimetre of rain	= 0.999,972 litres per square metre
	= 9.999,72 litres per hectare

Proportion: Volume Basis

Numbers

1 per cubic inch	= 0.061,023,74 per cubic centimetre
1 per cubic centimetre	= 16.387,064 per cubic inch (exactly)
1 per cubic foot	= 35.314,67 per cubic metre
1 per cubic metre	= 0.028,316,846,592 per cubic metre (exactly)
1 per cubic yard	= 1.307,951 per cubic metre
1 per cubic metre	= 0.764,554,857,984 per cubic yard (exactly)

Area

1 square foot per cubic inch	= 0.005,669,291 square metres per cubic centimetre
1 square metre per cubic centimetre	= 176.388,9 square feet per cubic inch
1 square yard per cubic yard	= 1.092,613 square metres per cubic metre
1 square metre per cubic metre	= 0.914,400,0 square yards per cubic yard

Volume

1 millilitre per Imperial gallon	=	0.219,975,3 millilitres per litre
1 millilitre per litre	=	4.545,965 millilitres per Imperial gallon
1 millilitre per U.S. gallon	=	0.264,179,4 millilitres per litre
1 millilitre pre litre	=	3.785,306 millilitres per U.S. gallon
1 Imperial fluid ounce per Imperial gallon	=	0.800,000,0 U.S. fluid ounces per U.S. gallon
1 U.S. fluid ounce per U.S. gallon	=	1.250,000 Imperial fluid ounces per Imperial gallon

Weight

1 gram per millilitre	=	0.999,972 grams per cubic centimetre
1 gram per cubic centimetre	=	1.000,028 grams per millilitre
1 gram per cubic foot	=	0.000,035,314,67 grams per cubic centimetre
1 gram per cubic centimetre	=	28,316.85 grams per cubic foot
1 gram per cubic yard	=	1.307,951 grams per cubic metre
1 gram per cubic metre	=	0.764,554,9 grams per cubic yard
1 avoirdupois ounce per Imperial gallon	=	6.236,195 grams per litre
1 gram per litre	=	0.133,522,7 avoirdupois ounces per U.S. gallon
1 avoirdupois pound per cubic foot	=	0.016,018,46 grams per cubic centimetre
1 gram per cubic centimetre	=	624.279,6 avoirdupois pounds per cubic foot
1 avoirdupois pound per Imperial gallon	=	0.099,779,13 kilograms per litre
1 kilogram per litre	=	10.022,14 avoirdupois pounds per Imperial gallon
1 avoirdupois pound per U.S. gallon	=	0.119,829,8 kilograms per litre
1 kilogram per litre	=	8.345,171 avoirdupois pounds per U.S. gallon

Temperature

a temperature of t°Fahrenheit	=	5(t-32)/9°Celsius or centigrade
a temperature of t°Celsius or centigrade	=	9t/5 + 32°Fahrenheit
a temperature of t°Kelvin	=	t-273.15°Celsius or centigrade
a temperature of t°Celsius or centigrade	=	t+273.15°Kelvin

Volume: Liquid Measure

Imperial

1 pint	=	20 fluid ounces
1 quart	=	2 pints
1 gallon	=	4 quarts
	=	160 fluid ounces

United States

1 pint	=	16 fluid ounces
1 quart	=	2 pints
1 gallon	=	4 quarts
	=	128 fluid ounces

Metric

1 millilitre	=	1.000,028 cubic centimetres (cc)
1 centilitre	=	10 millilitres (ml)
1 decilitre	=	10 centilitres (cl)
1 litre	=	10 decilitres (dl)
	=	1, 000 millilitres
1 decalitre	=	10 litres (l)
1 hectolitre	=	10 decalitres (dal)
1 kilolitre	=	10 hectolitres (hl)
1 myrialitre (mal)	=	10 kilolitres (kl)

Conversions between Imperial and Metric Measures

Basic relationships:

1 gallon	=	4.545,964,59 litres
	=	4,546.091,877 cubic centimetres
	=	277.411,779,8 cubic inches
1 minim	=	0.059,195,25 millilitres
	=	0.059,193,90 cubic centimetres
1 fluid ounce	=	28.412,28 millilitres
	=	28.413,07 cubic centimetres
1 millilitre	=	0.035,196,05 fluid ounces
1 pint	=	568.245,6 millilitres
	=	568.261,5 cubic centimetres
1 millilitre	=	0.001,759,803 pints
1 quart	=	1,136.491 millilitres
	=	1,136.523 cubic centimetres
1 millilitre	=	0.000,879,901,3 quarts
1 gallon	=	4.545,965 litres
	=	4,546.092 cubic centimetres
1 litre	=	0.219,975,3 gallons
1 cubic metre	=	219.969,2 gallons

Conversions between United States' and Metric Measures

Basic relationships:

1 gallon	=	231 international cubic inches (exactly)
	=	3.785,306 litres
	=	3,785.411,784 cubic centimetres (exactly)
1 millilitre	=	16.231,18 minims
1millilitre	=	0.270,519,7 fluid drams
1 fluid ounces	=	29.572,70 millilitres
	=	29.573,53 cubic centimetres

1 millilitre	=	0.033,814,97 fluid ounces
1 pint	=	473.1663,3 millilitres
	=	473.176,5 cubic centimetres
1 millilitre	=	0.002,113,435 pints
1 quart	=	946.326,5 millilitres
	=	946.352,9 cubic centimetres
1 millilitre	=	0.001,056,718 quarts
1 gallon	=	3.785,306 litres
	=	3,785.412 cubic centimetres
1 litre	=	0.264,179,4 gallons
1 cubic metre	=	264.172,1 gallons

Conversions between Imperial and United States' Measures

Basic relationships:

0.219,975,316 Imperial gallons	=	0.264,179,434 U.S. gallons
	=	1 litre
1 Imperial fluid ounce	=	0.960,760,3 U.S. fluid ounces
1 U.S. fluid ounce	=	1.040,842 Imperial fluid ounces
1 Imperial pint	=	1.200,950 U.S. pints
1 U.S. pint	=	0.832,673,9 Imperial pints
1 Imperial quart	=	1.200,950 U.S. quarts
1 U.S. quart	=	0.832,673,9 Imperial quarts
1 Imperial gallon	=	1.200,950 U.S. gallons
1 U.S. gallon	=	0.832,673,9 Imperial gallons

Volume: Solid Cubic Measure

English

1 cubic foot	=	1.728 cubic inches
1 cubic yard	=	27 cubic feet

Metric

1 cubic centimetre	=	1.000 cubic millimetres
1 cubic metre	=	1,000,000 cubic centimetres (cc)

Conversions

Basic relationships:

1 inch	=	2.54 centimetres (exactly)
1 cubic inch	=	16.387,064 cubic centimetres (exactly)
1 cubic centimetre	=	0.061,023,74 cubic inches
1 cubic foot	=	28,316.846,592 cubic centimetres (exactly)
1 cubic centimetre	=	0.000,035,314,67 cubic feet
1 cubic yard	=	0.764,554,857,984 cubic metres (exactly)
1 cubic metre	=	1.307,951,0 cubic yards

Special Timber Measures

6 board feet	=	1 cubic foot[a]
1 Hoppus cubic foot	=	1.273,239,6 cubic feet
	=	0.036,054,130 cubic metres
1 cunit	=	100 cubic feet of solid timber
1 cord[b]	=	128 cubic feet[b]
	=	3.624,556 cubic metres[b]
1 Petrograd standard	=	165 cubic feet
	=	4.672,280 cubic metres
1 Gothenburg standard[a]	=	180 cubic feet[b]
	=	5.097,032 cubic metres[b]
1 fathom[b]	=	216 cubic feet[b]
	=	6.116,439 cubic metres[b]
1 stère[b]	=	1 cubic metre

[a] theoretical equivalence only, not a processing conversion
[b] overall measures of stacked or piled wood

Weight

Avoirdupois

32 drams	=	875 grains (gr)
1 ounce	=	16 drams
1 pound	=	16 ounces (oz)
	=	7,000 grains
1 stone	=	14 pounds (lb)
1 quarter	=	2 stones (st) = 28 pounds
1 short hundredweight	=	100 pounds
1 long hundredweight	=	4 quarters (qtr) = 8 stones
	=	112 pounds
1 short ton	=	20 short hundredweights
	=	2,000 pounds
1 long ton	=	20 long hundredweights
	=	2,240 pounds

Metric

1 milligram	=	1,000 micrograms (µg)
1 centigram	=	10 milligrams (mg)
1 decigram	=	10 centigrams (cg)
1 gram	=	10 decigrams (dg)
	=	1,000 milligrams
1 decagram	=	10 grams (g)
1 hectogram	=	10 decagrams (dag)
1 kilogram	=	10 hectograms (hg)
	=	1,000 grams
1 myriagram	=	10 kilograms(kg)
1 quintal	=	100 kilograms
1 metric ton, or tonne	=	10 quintals = 1,000 kilograms

Conversions

Basic relationships:

1 avoirdupois grain	=	1 international grain
	=	0.064,798,91 grams (exactly)
1 international avoirdupois pound	=	0.453,592,37 kilograms (exactly)

Between Avoirdupois and Metric Measures

1 grain	=	0.064,798,91 grams (exactly)
1 gram	=	15.432,36 grains
1 dram	=	1.771,845,195,312,5 grams (exactly)
1 gram	=	0.564,383,4 drams
1 ounce	=	28.349,523,125 grams (exactly)
1 gram	=	0.035,273,96 ounces
1 pound	=	0.453,592,37 kilograms (exactly)
1 kilogram	=	2.204,623 pounds
1 stone	=	6.350,293,18 kilograms (exactly)
1 kilogram	=	0.157, 473,0 stones
1 quarter	=	12.700,586,36 kilograms (exactly)
1 kilogram	=	0.078,736,52 quarters
1 short hundredweight	=	45.359,237 kilograms (exactly)
1 kilogram	=	0.022,046,23 short hundredweights
1 long hundredweight	=	50.802,345,44 kilograms (exactly)
1 kilogram	=	0.019,684,13 long hundredweights
1 short ton	=	0.907,184,74 metric tons (exactly)
1 metric ton	=	1.102,311 short tons
1 long ton	=	1.016,0466,908,8 metric tons (exactly)
1 metric ton	=	0.984,206,5 long tons