

A Climate Change Threshold for Forest Dieback in the African Sahel

Meeting “Understanding Ecological Thresholds in Global Change: Connecting Science to Decisions and Response”

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Introduction

Increasing aridity has degraded ecosystems and human well-being during the 20th and 21st Centuries across the Sahel, an ecological zone of wooded savanna that stretches 6000 km across Africa. Climate change has initiated a concatenation of negative impacts, starting with a significant decrease in precipitation. In turn, the decrease in precipitation has caused a dieback of mesic forest species and loss of forest biodiversity. At the same time, deforestation and overgrazing have intensified the reduction in vegetation cover. Forest dieback has shifted the Sahel, Sudan, and Guinea ecological zones latitudinally as the range of xeric forest species has expanded southward. The shift of ecological zones has altered natural habitats and reduced the provision of ecosystem services, including soil erosion control, production of wood and non-wood forest products, forest carbon sequestration, and biodiversity conservation. The long-term decline in forest species richness and tree densities in the Sahel show that the decline in precipitation has caused desertification—land degradation characterized by a decline in potential ecosystem productivity.

Forest dieback fuels three positive feedback mechanisms: reduction of the evapotranspiration inputs necessary for the northward advance of the summer monsoon rains that sustain vegetation and forestall desertification, increases in the greenhouse gas emissions that cause the reduction in rainfall, and reduction of the forest biodiversity that strengthens ecosystem resilience to long-term drought. Consequently, three global environmental phenomena—climate change, desertification, and loss of biodiversity—interact strongly in the Sahel.

The loss of ecosystem services has damaged the ability of local people to survive. Ultimately, famine and the death of up to a quarter of a million people in the Sahel drought of 1968-1973 forced international development agencies to finance short-term relief and long-term assistance. This paper examines climate change and forest dieback in the Sahel as a case of a threshold response of an ecosystem to climate change and a threshold response of human society to ecological change, using the template developed for the Heinz Center-Nature Conservancy meeting “Understanding Ecological Thresholds in Global Change: Connecting Science to Decisions and Response.”

Climate Change and Desertification

Increasing rainfall and decreasing evapotranspiration towards the Equator differentiates vegetation in the northern tropics of Africa into five latitudinal bands of increasingly mesic species: the ecological zones of the Sahara (desert), the Sahel (wooded savanna), the Sudan (woodland), Guinea (deciduous forest), and Congo (rainforest) (Aubrevillé 1950, White 1983) (Figure 1). This paper concentrates on the Sahel, Sudan, and Guinean ecological zones, which have experienced significant ecological changes in the past century.

Thorny tree species with small, deciduous, sclerophyllous, and bipinnately compound leaves characterize the Sahel. Trees occur singly and widely-spaced with small groves occurring in some cemeteries and interdunal valleys. In the Sudan, trees collect in small groves and form dense thickets in low-lying seasonal ponds and fossil valleys. Trees form an open layer 8-20 m height. Most Sudanian tree species possess pinnately compound leaves with leaflets larger than Sahelian species and produce dense, slightly sweet fruits. In the Guinean zone, mesic species form a closed-canopy broad-leaved deciduous forest. High precipitation and insolation offer Guinean vegetation an energy surplus that many forest species allocate to the production of dense timber or succulent fruit.

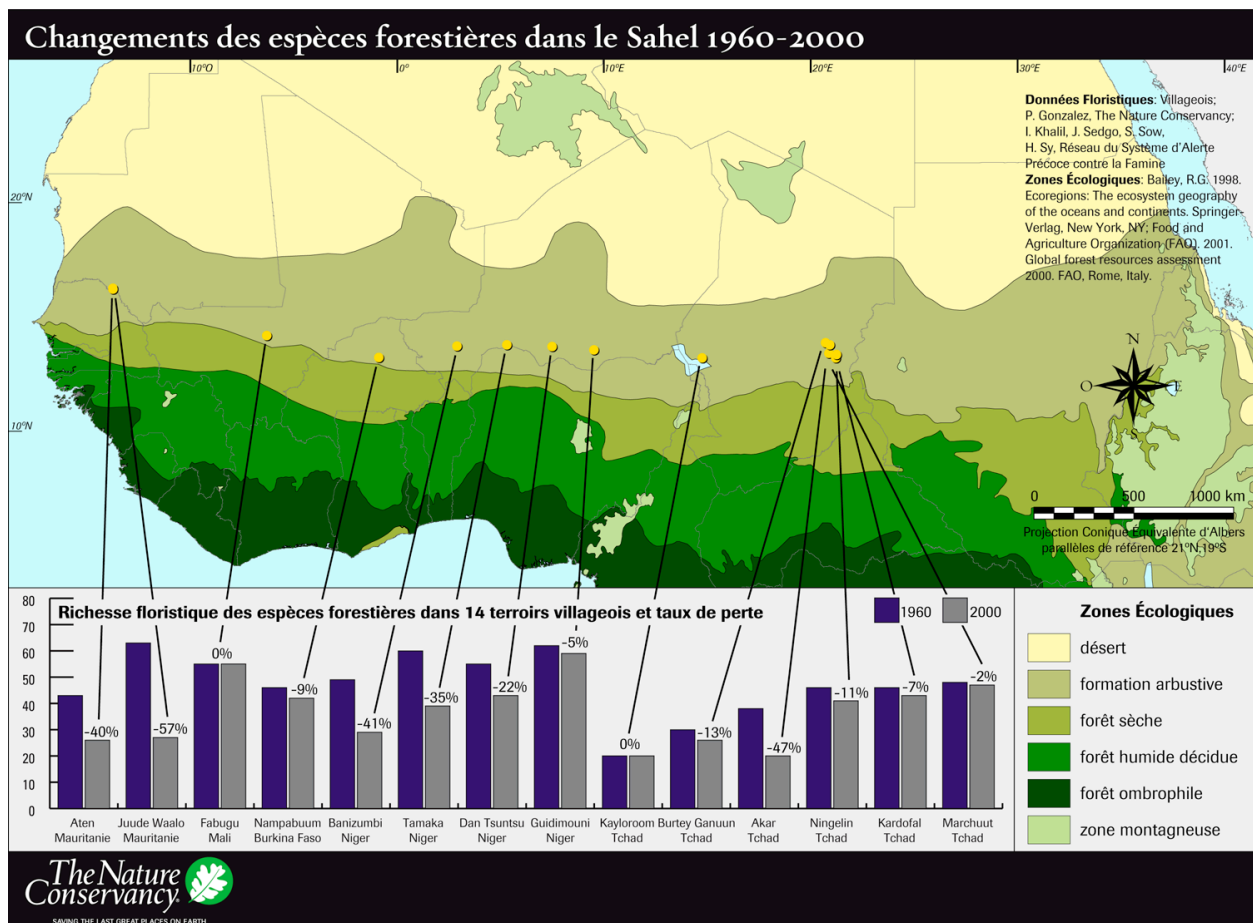


Figure 1. Forest species changes in Africa, 1960-2000. Ecological zones, from north to south: Sahara Desert (*désert*), the Sahel (wooded savanna (*formation arbustive*)), the Sudan (woodland, (*forêt sèche*)), Guinea (deciduous forest, (*forêt humide décidue*)), Congo (rainforest (*forêt ombrophile*)), mountain zones (mountain formations (*zones montagneuses*)) (Gonzalez et al. 2004).

Biodiversity increases from north to south, with tree species richness increasing from approximately 30 species in the north to 300 species in the south (Berhaut 1967, Gonzalez 2001). Wildlife progresses from paleotropical migrant birds in the Sahel to an array of mammals that culminates with giraffes, lions, and elephants in the Guinean zone. Agricultural fields and livestock pastures occupy significant areas of the Sahel and the Sudan while timber harvesting occurs in the Guinean zone. A modest network of wildlife reserves, national forests, and national parks protects significant savanna, forest, and wetland habitats.

The Sahel has experienced the most substantial decline in rainfall recorded in the world within the period of instrumental measurements (Diouf et al. 2000, Hulme 2001, Dai et al. 2004). In the 20th Century, precipitation over the Sahel declined up to 30%. The longest record of precipitation measurements in Africa, the 148-year time series at St. Louis (Ndar), Senegal, shows a statistically significant ($p < 0.0001$) decline in rainfall since the 19th Century (Figure 2). Mean annual surface temperature in the Sahel increased up to 1°C in the 20th Century (Hulme et al. 2001), a rate of increase double the global rate (IPCC 2001a), increasing potential evapotranspiration and aridity.

Precipitation over the Sahel originates in warm, humid air issuing from the Saint Helena high pressure cell over the south Atlantic Ocean during the northern hemisphere summer (UNCOD 1977). The warm air organizes into

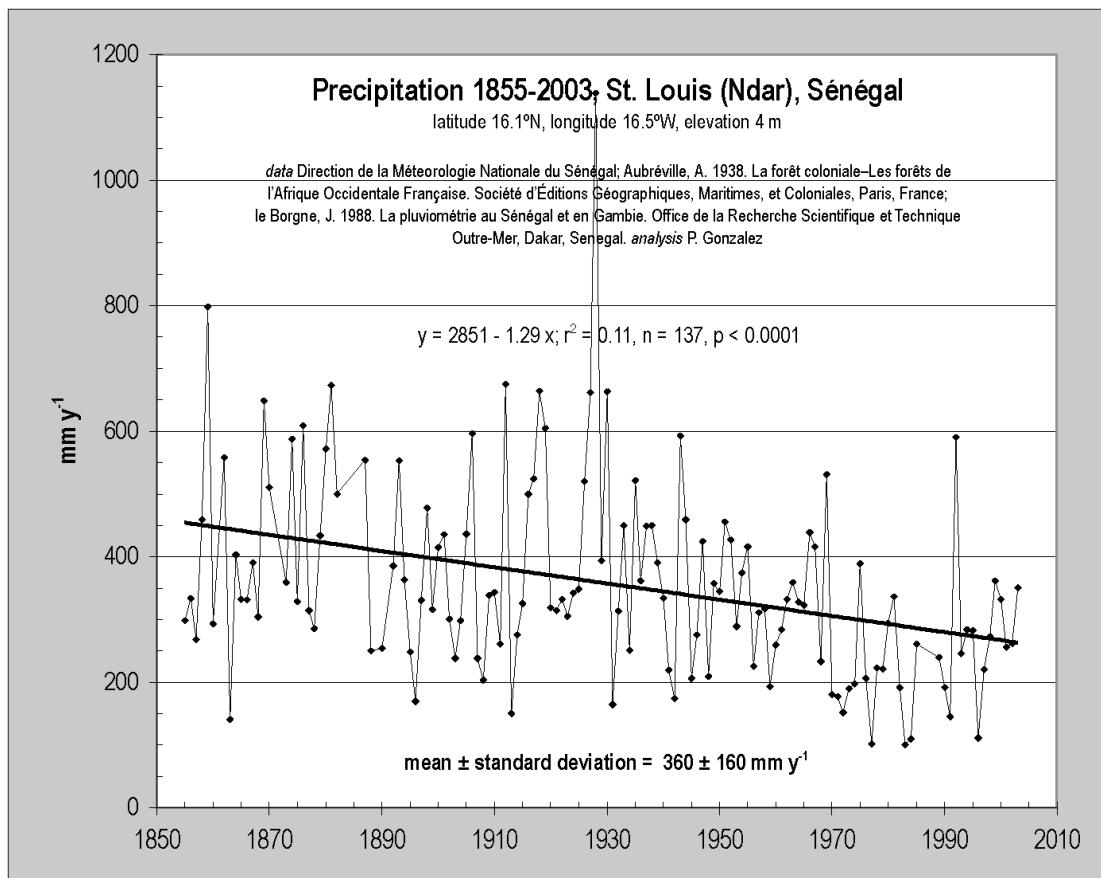


Figure 2. Precipitation 1855-2003 at St. Louis (Ndar), Senegal. Linear regression shows a statistically significant ($p < 0.0001$) decline during the 148 year period. (Data Aubréville 1938, le Borgne 1988, Direction de la Météorologie Nationale du Sénégal. Analysis Gonzalez 2001.)

the African monsoon, which moves north and brings rain onshore to the Congo and Guinean zones. The African monsoon continues north and feeds the Inter-Tropical Convergence Zone (ITCZ), the band of convergence of the northeast and southeast trade winds. The ITCZ creates convective rainstorms as it migrates north after the Summer Solstice and returns south after the Autumnal Equinox (Charney 1975). The African easterly jet stream and the Tropical easterly jet stream deflect the African monsoon to a southeast-northwest orientation and create storms that propagate westward along the ITCZ (Carlson 1969). These storms bring rain to the Sudan and the Sahel. As the disturbances move off the west coast of Africa, they spawn tropical depressions that may eventually build up to hurricanes as they approach the Caribbean.

Analyses of observed rainfall and sea-surface temperature patterns and coupled atmosphere-ocean-land-vegetation model output indicates that the Sahel drought results from climate change-induced increases in sea surface temperature amplified by a reduction of Sahel vegetation cover (Giannini et al. 2003, Zeng 2003.) Climate change has increased sea surface temperatures in the south Atlantic Ocean and the Indian Ocean (Rayner et al. 2006). These increases in sea surface temperature initiated a decline in Sahel rainfall (Lamb 1978, Giannini et al. 2003). A reduction in vegetation cover in the Sahel maintains and reinforces the decline in rainfall through two positive feedback mechanisms—between precipitation and surface reflectance (albedo) (Charney 1975, Xue and Shukla 1993) and between precipitation and vegetation (Aubréville 1949, Taylor and Lebel 1998, Zeng et al. 1999, Wang and Eltahir 2000).

Field research across a 7600 km² area in Senegal that spans the Sahel, Sudan, and Guinea ecological zones showed that the long-term reduction in rainfall has caused forest dieback and shifted the three zones 25-30 km south in the period ca. 1945-1993 towards areas of higher precipitation (Gonzalez 2001). The research compared data on the 126 tree and shrub species in the area from field surveys and forest inventories of 20 400 trees in a grid of 135 1-hectare plots with data from systematic surveys of one male elder in each of 135 villages. Corrections to ca. 1945 recollections by male peers in group discussions or individual conversations, corrections to ca. 1945 and 1993 data made by female elders, and corrections made from direct observations of 1993 species distributions amounted to only 1% of 34 020 data points.

Results showed a statistically significant ($p < 0.001$) decline in forest species richness from 64 ± 2 species per 4 km² to 43 ± 2 species per 4 km² in the period ca. 1945-1993 (Gonzalez 2001). Xeric Sahel species expanded in the north, tracking a concomitant retraction of mesic Sudan and Guinean species to the south (Figure 3). Guinean and Sudan species experienced the greatest decrease in geographic range. Ecological zones shifted towards areas of higher rainfall 25-30 km at an average rate of 500-600 m y⁻¹, less than the approximate maximum dispersal limit of most forest species of 1.5 km y⁻¹ (Davis and Shaw 2001, Malcolm et al. 2001).

Analyses of aerial photographs quantified the magnitude of the forest dieback. Manual counts of a sample of 324 000 trees of height ≥ 3 m in 137 aerial photos taken in 1954 by the Institut Géographique National of France and in 83 aerial photos taken in 1989 by the Japanese International Cooperation Agency showed a statistically significant

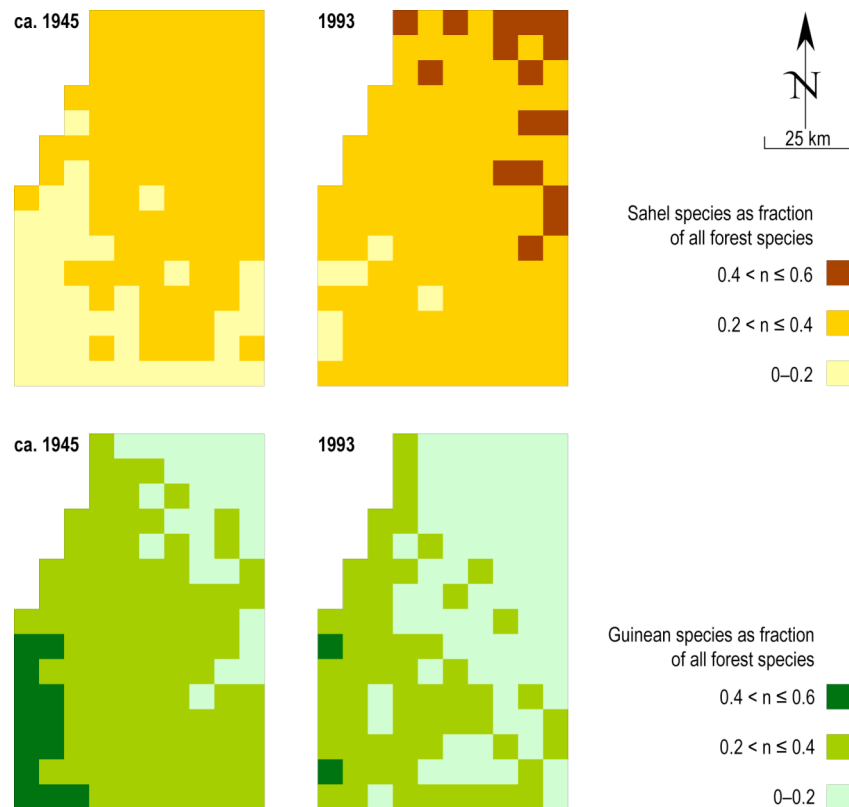


Figure 3. Shift of the Sahel and Guinea ecological zones in northwest Senegal in the period ca. 1945-1993 (Gonzalez 2001).

($p < 0.001$) decline in tree density from 10 ± 0.3 trees ha^{-1} to 7.8 ± 0.3 trees ha^{-1} (Gonzalez 2001). The fall in species richness of $33 \pm 5\%$ in 48 years and the decrease in tree densities of $23 \pm 5\%$ in 35 years both occurred at a rate of -0.008 y^{-1} . Further analyses of 1954 aerial photographs and 2002 1-meter spatial resolution panchromatic IKONOS satellite images of three 200 km^2 areas in Senegal and Mauritania are in progress (Figure 4).

Multivariate statistical analyses of 215 ecological and socioeconomic independent variables and 15 dependent variables on forest species richness and tree density identified rainfall and temperature as the most significant factors explaining the variance in the distribution, densities, and changes in trees and shrubs in the research area (Gonzalez 2001). Factors related to local population growth did not explain observed forest dieback.

Other research at individual sites in Senegal (Poupon 1980, Lericollais 1988, Frankenberg and Anhuf 1989) confirmed the loss of mesic tree species and decrease in tree densities in the 20th Century. Analysis of additional forest species inventories and surveys of elders in 14 villages in Burkina Faso, Chad, Mali, Mauritania, and Niger showed decreases in species richness of up to 57% in the period 1960-2000 (Gonzalez et al. 2004) (Figure 1). This demonstrates that forest dieback has occurred across the Sahel.

Annual monitoring from 1970 to 1975 of every single tree in a 25 ha site at Fete Ole in the Senegal Sahel showed that the Sahel drought of 1968-1973 seemed to initiate the forest dieback (Poupon 1980). Annual tree mortality started increased in 1972 from a negligible fraction to over 50%. This suggests that the 1968-1973 drought, the most severe drought recorded in 150 years, moved Sahel ecosystems past a climate threshold of aridity. Although

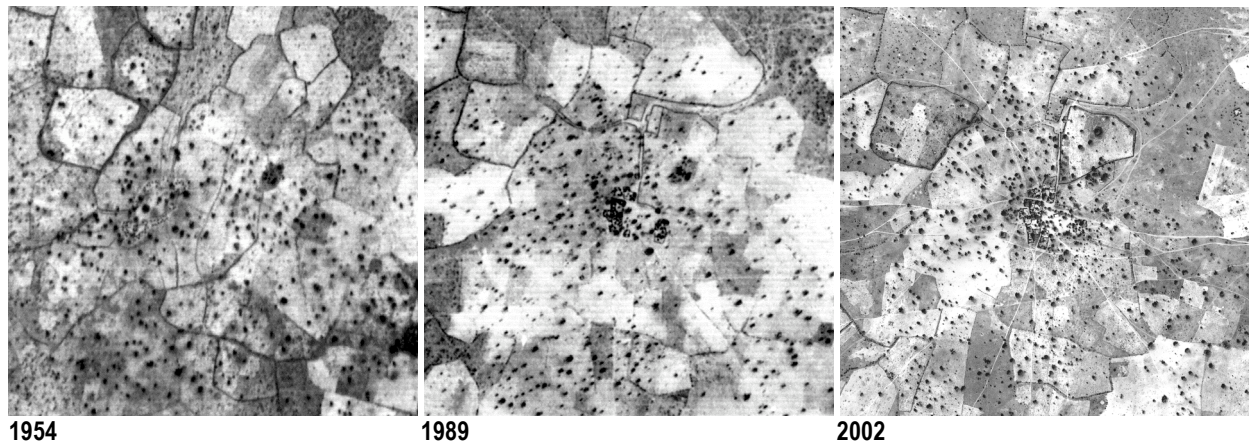


Figure 4. Aerial photographs (1954, 1989) and IKONOS image (2002) of 1 km square around Yamaan Sekk, northwest of Njóobéen Mbataar, Senegal. Dark lines are live hedges of *Euphorbia balsamifera*. Dots are mature trees of $h \geq 3$ m. Tree density in the surrounding region decreased 25% between 1954 and 1989. Forest dieback slowed between 1989 and 2002. (Images Institut Géographique National de France (1954), Japanese International Cooperation Agency (1989), Space Imaging (2002)).

precipitation had been declining throughout much of the 20th Century, massive forest dieback did not occur until the early 1970s, after 4-5 years of rainfall that fell more than one standard deviation below the long-term mean. Ecosystems exhibited resilience to a significant increase in aridity up until the 1968-1973 drought. Initial analyses of IKONOS images indicates that forest dieback slowed in the 1990s (Figure 4). The remaining forest cover retains a certain level of resilience, but a drought as severe as the 1968-1973 has not yet reoccurred.

Sahel ecosystems may have moved to a different state of low ecological productivity characteristic of desertification. The 1981-2003 Normalized Difference Vegetation Index (NDVI) remote sensing time series shows that increased rainfall in the period 1998-2003 did not increase vegetation productivity in 2003 above 1981 levels (Anyamba and Tucker 2005). Rain use efficiency also declined in the same period (Hein and De Ridder 2006). These trends contradict the normal increase of tree cover in savannas as precipitation increases (Sankaran et al. 2005).

General circulation models (GCMs) project that climate change will continue to raise temperature and decrease precipitation across the Sahel (Hulme et al. 2001, Held et al. 2005). Projected changes from GCMs under the IPCC SRES A2 emissions scenario (IPCC 2000) indicate that the Sahel, Sudan, and Guinea could experience mean annual temperature increases of 2–6°C and precipitation declines of up to 50% by 2080 AD (Hulme et al. 2001). These future changes threaten to continue to shift vegetation zones (Scholze et al. 2006).

Desertification is a process of land degradation characterized by a “reduction or loss, in arid, semi-arid, and dry sub-humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands” (UNCCD 1994). The long-term decline in forest species richness and tree densities show that the decline in precipitation has caused desertification in the Sahel.

Climate change exacerbates desertification through increasing temperature and decreasing rainfall. Conversely, desertification aggravates climate change through the emission of greenhouse gases from cleared and

dead vegetation and through the reduction of the carbon sequestration potential of desertified areas (IPCC 2001b). Forest dieback in northwest Senegal in the period 1956-1993 caused standing biomass to fall 2 t ha^{-1} , releasing 0.9 t ha^{-1} of carbon at a rate of $60 \text{ kg C person}^{-1} \text{ y}^{-1}$ (Gonzalez 2001).

Impacts of desertification in the Sahel have reached into the western hemisphere. Reduced vegetation cover has increased wind erosion, and the transport of dust across the Atlantic Ocean into the Caribbean Sea, where the dust has contributed to coral reef dieback (Shinn et al. 2000, Prospero and Lamb 2003).

In northwest Senegal, significant dieback among the two shrub species that local Wolof villages use for firewood has decreased human carrying capacity to below actual population densities. The 1993 rural population density of $45 \text{ people km}^{-2}$ exceeded the carrying capacity of shrubs of $13 \text{ people km}^{-2}$ (min 1, max. $21 \text{ people km}^{-2}$) (Gonzalez 2001). Moreover, over 25 species used in traditional medicine have diminished significantly. In addition, eight species that provided fruit, leaves, and gum in past droughts, such as Déem (*Zizyphus mauritiana*) and Mbép (*Sterculia setigera*) have disappeared from as much as 53% of their range.

The Sahel drought of 1968-1973 reduced vegetation cover and agricultural yields so significantly that it caused the death of up to a quarter of a million people (UNCOD 1977). The famine occurred abruptly in the early 1970s, after 4-5 years of rainfall that fell more than one standard deviation below the long-term mean. Other factors, including foreign raids that captured and placed Africans in slavery up to the 19th Century, French and British colonial rule through 1960, Portuguese colonial rule through 1975, civil conflict and political unrest after independence, government corruption, population growth, agricultural subsidies, deforestation, and overgrazing also led to the famine.

The fraction of the population that lives in conditions of food insecurity has not changed significantly since the 1970s (Rosegrant et al. 2005). The Millennium Ecosystem Assessment (2005) projected that desertification will persist or get worse under all future scenarios that it examined.

Institutional Responses to Environmental Change

The death of up to a quarter of a million people following the Sahel drought of 1968-1973 highlights the grave order of the threshold that Sahel ecosystems crossed and a social threshold beyond which existing institutions could not adequately respond to avert disaster.

In response to the famine, nine countries (Burkina Faso, Cape Verde, Chad, The Gambia, Guinea-Bissau, Mali, Mauritania, Niger, and Senegal) in 1973 established a regional organization, the *Comité Permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel* (CILSS) (Permanent Interstate Committee for Drought Control in the Sahel). CILSS operates three institutions: a political secretariat, a scientific research center (*Centre Régionale AGRHYMET*), and a socio-economic research center (*Institut du Sahel*). These institutions established several new systems that seek to avert future catastrophic impacts of environmental change in the Sahel. The CILSS Secretariat gathers political leaders at periodic meetings to coordinate natural resource management policies. The *Centre*

Régionale AGRHYMET collects and analyzes natural resource data and operates an early warning system to provide alerts of potential drought and of locust outbreaks. The *Institut du Sahel* conducts a small program of socio-economic research focused on the Sahel.

Individual countries responded to the drought by attempting to invest in government programs in natural management, including programs for agriculture, biodiversity conservation, fisheries, forestry, livestock, and water resources. Most countries operate an entire cabinet-level ministry dedicated to each of these sectors, although the ministries generally existed prior to 1973.

Bilateral international development assistance, particularly from the Canada, France, Germany, Japan, Italy, the Netherlands, Norway, Sweden, and the United States, and multilateral development assistance, particularly from the European Union, the United Nations Development Programme, the World Bank, and the World Food Programme, significantly increased after 1973. International development assistance to the Sahel countries increased from \$500 million (1990 dollars) in 1970 to \$2.5 billion (1990 dollars) in 1994 (Naudet 1998). This represents an increase of aid to the Sahel as a fraction of total international development assistance from 2.5% in 1970 to 5% in 1994. In 1976, the Organization for Economic Cooperation and Development (OECD) established an institution, the *Club du Sahel*, that raises funding specifically for Sahel countries.

International development assistance has funded projects in all sectors, including education, health, industry, natural resources, and telecommunications. Natural resource projects have generally evolved from programs designed by foreigners that used imported ideas and materials to participatory, integrated, and locally-planned and implemented programs. For example, many early forestry projects destroyed local vegetation to establish industrial plantations of exotic species. Contemporary forestry projects engage in participatory land-use planning that conserves undisturbed local ecosystems and promotes natural regeneration and integrated agro-sylvo-pastoral management of settled areas.

At the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro, Brazil, countries negotiated conventions to address three principal global environmental problems. The conventions included the U.N. Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), and the U.N. Convention to Combat Desertification (UNCCD). Parties to the convention, including Sahel countries, agreed to develop plans to achieve the goals of each convention: National Adaptation Programmes of Action (UNFCCC NAPA), National Biodiversity Strategy and Action Plans (CBD NBSAP), National Action Plans (UNCCD NAP). These documents comprise integrated plans to respond to each of the global environmental phenomena that have caused forest dieback and other ecological impacts in the Sahel.

Sahel countries and foreign partners have established a vast network of national and regional institutions to avert ecological disaster such as the tragic death of the Sahel drought of 1968-1973. Although these institutions have developed a safety net of last resort, they need to make more progress on sustainable natural resource management, biodiversity conservation, and the restoration of ecosystem function across the Sahel.

Coping Strategies

Local people across the Sahel are adapting to the changing climate by resurrecting natural resource management practices that were common before subsidized export agriculture. Farmers and herders have traditionally adapted to arid conditions by promoting the natural regeneration of trees and shrubs. Natural regeneration is a practice in which farmers and herders set aside entire parcels of land or select small trees in agricultural fields and pastures, protect the trees, prune them to promote rapid growth of the apical meristem, and raise them to maturity. The practice requires no special inputs and encourages the propagation of well-known, multiple-use trees. Young trees that germinate in the field are more adapted to harsh climate conditions and livestock browsing than planted trees. Ultimately, only natural regeneration can cover an extensive surface area, a condition necessary not only to map a comprehensive system of natural resource management, but also to engage positive climatic effects.

The Sereer in Senegal (Lericollais 1988) and the Mossi in Burkina Faso (Kessler 1992) have doubled tree densities of *Acacia albida* and *Butyrospermum parkii*, respectively, in areas cultivated during the rainy season and grazed by livestock in the dry season. In Northwest Senegal, small trees ($h < 40$ cm) occur at a density of 160 ± 18 trees ha^{-1} , over 20x the density of adult trees ($h \geq 3$ m) (Gonzalez 2001). Because drought-tolerant Sahel species account for 37% of small trees, natural regeneration under current climatic conditions could potentially reconstitute the vegetation cover.

Traditional livestock herding practices also reduced the risk of overgrazing, land degradation, and the reduction of habitat for gazelles and other wildlife (Breman and De Wit 1983, Hein 2006). Traditional herders generally kept stocking rates low and moved herds when forage became low. They avoided concentrating livestock for extended periods in the same location. These practices contributed to the development of a nomadic way of life for many herding ethnic groups.

Although local tree species are better adapted to the harsh climate of the Sahel, one exotic species from India, *Azadirachta indica* (*niim*), has succeeded as a shade tree in village compounds across the Sahel. The species has now become naturalized in parts of Africa. It provides deep shade and small poles for fences and huts.

In order to ease the workload for women and to reduce deforestation, international development agencies have promoted fuel-efficient wood stoves. In Senegal, a modest number of households have fashioned *ban ak suuf* cooking stoves out of local clay and straw. This stove is a horseshoe-shaped hearth that wraps around a kettle to channel heat more efficiently than an open fire. Several projects have also trained local blacksmiths to make a portable charcoal stove called the *sakkana* from metal and ceramic for urban households. In addition to the primary benefits for women and forest cover, improved cook stoves improve energy efficiency, reduce greenhouse gas emissions, and reduce health problems from particulates and smoke.

The modest network of wildlife reserves, national forests, and national parks across the Sahel, Sudan, and Guinea often lacks funding for basic operations. Some of these protected areas engage in landscape planning that

includes local people engaged in agriculture, fishing, and livestock herding in surrounding areas. No unit has yet systematically integrated climate change factors in conservation planning. Effective climate change adaptation and mitigation strategies will require practices that address ecological change and the improvement of rural livelihoods.

In conclusion, Sahel ecosystems have crossed a climate threshold of aridity in an abrupt, nonlinear manner (Burkett et al. 2005). Monitoring key ecological parameters could help warn natural resource managers of future thresholds so that they can facilitate preemptive responses or simply evaluate the effectiveness of current management practices (Groffman et al. 2006). The interaction of climate change, desertification, and loss of biodiversity, as well as the complex social, economic, and political factors that lead to forest dieback and other ecological changes in the Sahel present difficulties in monitoring and foreseeing future threshold behavior. Nevertheless, any reduction in greenhouse gas emissions and any increase in vegetation cover will reduce the risk of future catastrophic ecological change in the Sahel.

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