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Forest Sector
Outlook

Innovative forestry for a sustainable future

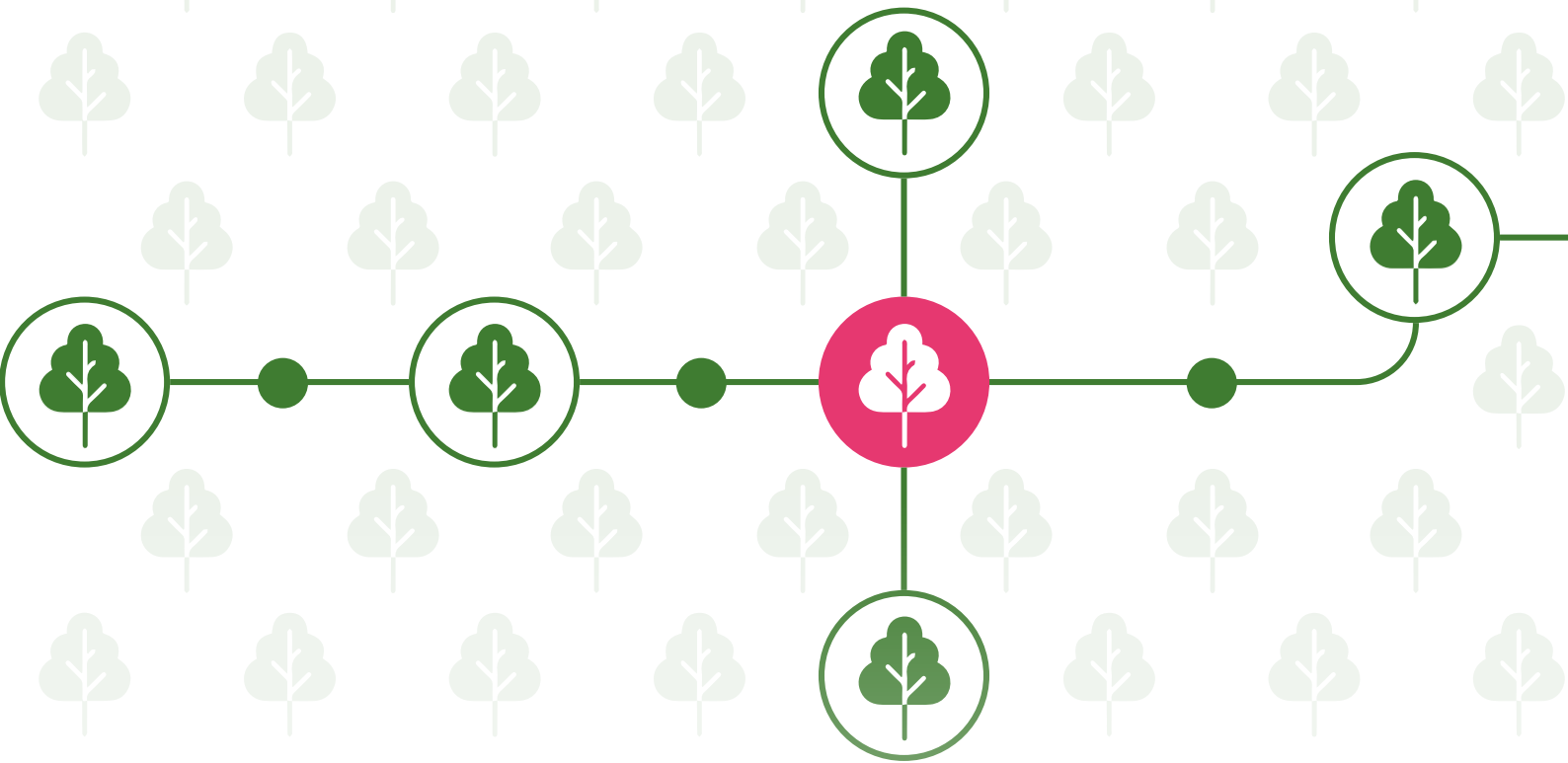
Youth contributions
from Asia and the Pacific

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Foreword

More than ever forests are called upon to address the great challenges of our times: climate change, biodiversity erosion, poverty, food insecurity. Conflicting demands and pressures are particularly acute given strong demographic pressure, economic growth and increasing impacts of climate change. To answer competing demands, protect and sustainably manage natural resources while increasing production of ecosystem goods and services, while simultaneously maintaining and strengthening sustainable agriculture, foresters need to innovate.

As shown by FAO's Third Asia-Pacific Forest Sector Outlook Study (FAO, 2019), the uptake and scaling-up of innovative technologies in the forest sector in the Asia-Pacific region can support sustainable forest management with more accurate and reactive monitoring and reporting; enhanced transparency and participation in decision-making, empowering local and small actors. Innovative technologies can contribute to increase productivity, profitability and reduce operational costs; increase energy- and resource-use efficiency, reduce waste, enhance re-use and recycling, for low-carbon and circular bio-economies, reducing the pressure on natural forests. They create new products and services, new income opportunities; innovative, greener and safer jobs, making the forest sector more attractive for young people.

FAO and CIFOR, lead center of the CGIAR research programme on Forests, Trees and Agroforestry (FTA), are developing a roadmap on the application of innovative technologies

in the forest sector in Asia and the Pacific to enhance sustainable forestry and sustainable forest management. This roadmap is being developed through a participative process involving a wide range of key regional stakeholders and technical experts from governments and intergovernmental organizations, private sector, civil society organizations, academia and research institutions.

Young students and people, formally or informally engaged in the forest sector, will be the guardians and managers of tomorrow's forests. Technology savvy, the youth can play an instrumental role in the uptake and scaling-up of innovative technologies (whether digital technologies, biological technologies, technical innovations on processes and products, or innovative finance and social innovations), able to advance sustainable development in the forest sector in the region. Young people can bring in the innovation debate forward-looking perspectives and out-of-the-box thinking.

This is why FAO and CIFOR/FTA decided to strengthen their voice in the debate, relaying their experiences and propositions for sustainable innovation in the forest sector. This FAO and CIFOR co-publication gathers 13 youth contributions, carefully selected. These contributions illustrate, in various contexts, the potential of innovative technologies to advance sustainable forestry and sustainable forest management in the Asia-Pacific region.

We hope that this document provides useful food for thoughts for policy makers, investors,

researchers and practitioners to enhance innovation in forest monitoring, forest management and along forest value chains, in big companies or in small-scale enterprises, at regional and national levels or in local

communities. We hope it will help open new perspectives, create new opportunities, and address the economic, social and environmental challenges each actor faces in his/her own specific context.

On behalf of FAO



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On behalf of CIFOR



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Innovative forestry for a sustainable future

Youth contributions from Asia and the Pacific

Introduction

This publication assembles selected papers prepared by youth from the Asia-Pacific region on innovative forest technologies and their contribution to sustainable forestry and sustainable forest management.

Asia-Pacific roadmap on innovative forest technologies: elements of context

The 'Third Asia-Pacific Forest Sector Outlook Study' (APFSOS III: FAO, 2019), launched in June 2019 at the Asia-Pacific Forestry Week in Incheon, Republic of Korea, expressed concerns about the status, trends and future outlook for primary forest conservation and noted the importance of innovative technologies for sustainable forestry and sustainable forest management. The study highlighted that the uptake and scaling-up of innovative technologies creates significant opportunities and challenges for sustainable forestry and sustainable forest management

in the Asia-Pacific region¹. Nearly 300 forestry students and young professionals from more than 30 countries, consulted for this Outlook Study, found that the uptake of innovative technologies in the forest sector has been too slow and called for better opportunities for young people to learn and apply them.

Following-up on this important outlook study, FAO and CIFOR, lead center of the CGIAR research programme on Forests, Trees and Agroforestry (FTA), are jointly developing a roadmap on innovative forest technologies, including digital technologies, biological technologies, technical innovations on processes and products, innovative finance and social innovations. This roadmap is being developed through a participative process involving a wide range of key regional stakeholders and technical experts from governments and intergovernmental organizations, private sector, civil society organizations, academia and research

1 In terms of: regional cooperation, additional investments, infrastructure development, institutional changes, research and development, education and capacity building.

institutions. Two online expert workshops were organized around this roadmap: the first one, in July 2020, to launch the whole process and start building a strong community around it; and the second, in November-December 2020, focusing on innovative technologies. The detailed results of these workshops have been published online (Pingault et al., 2020, 2021).

Call for youth contributions: description of the process

Young people have shown their capacity to generate and spearhead trans-national mobilization to address environmental challenges, such as climate change, and advance sustainable development. They can be instrumental in shaping a sustainable future, including: by taking leadership roles and generating momentum through collaboration and social media, by transforming rigid institutions from within and participating to the uptake and upscale of innovative technologies in the forest sector (FAO, 2019).

This is why FAO and FTA decided to encourage students and young professionals to contribute actively to the roadmap. A call for abstracts was organized in Autumn 2020 (19 October – 15 December) to invite contributions from students and young people engaged in formal or informal activities linked to the forest sector in the Asia-Pacific region. This call was directed to candidates of 18-35 years old, citizens or residents of countries or territories of the Asia-Pacific region.

Seventy-one abstracts were received. The abstracts submitted were very diverse. They were carefully screened and evaluated by a team of CIFOR/ICRAF experts, based on a set of criteria including: clarity, originality and potential for transformative impact on the forest sector in the region. Some of the authors of the selected abstracts were invited to participate to the November 2020 expert workshop on innovative technologies where they made very valuable contributions and brought their unique forward-looking perspective (Pingault et al., 2021).

Twenty of the youth authors were selected to develop a full paper. They were invited to focus on the main challenges and opportunities associated with the application of innovative technologies in the forest sector in the region, highlighting the transformations² needed to enhance technology transfer and dissemination and to ensure that these technologies effectively contribute to sustainable development. Each paper was carefully reviewed by a committee of CIFOR/ICRAF experts, based on criteria including: the logical flow and clarity of the narrative, even for non-specialist readers, the scientific quality of the paper or the “field” insights it provides on a specific situation/context.

Content and organization of this document

This publication presents the 13 papers that went through the whole process of abstract submission, drafting, paper submission, review, revision, edition and final validation. These papers serve as technical inputs for the development of the roadmap. The papers are ordered in this publication, following the forest value chain: starting from the monitoring of deforestation, of forest degradation or of various forest characteristics; studying then innovations in forest management practices; and focusing finally on wood-based materials and other products and services.

Bahar and Wicaksono (#1)³ illustrate, with three concrete examples from Malaysia and Indonesia, how digital technologies (online platforms and mobile applications) can help effectively engage youth in satellite-based tropical forest monitoring. Focusing on seven districts in Nepal, Lama et al. (#2) show how Forest Watcher, a mobile application, can be used to facilitate and

2 Numbers between brackets refer to the order of the contribution in this publication.

3 The geographical scope of the roadmap, referred to in this technical paper as the “Asia-Pacific region”, covers 49 countries and territories, and is detailed in a note accessible online: https://www.foreststreesagroforestry.org/wp-content/uploads/2020/10/FAO-FTA_Roadmap-Note-on-geographical-scope_DEF.pdf

improve forest monitoring and reporting, enhance community-forest management, and strengthen local communities' participation in forest conservation. Sarzynski et al. (#3) demonstrate how Google Earth Engine can be used to ease the access to and analysis of millions of satellite images and to monitor, with high accuracy and in near real-time, oil palm and cashew plantations encroachment on forests in Indonesia and India. De Jesus (#4) suggests that combining various innovative digital technologies, for data collection, analysis, modelling and dissemination, in a "Snitch" open online platform, could provide new perspectives on how to raise awareness on the multiple impacts of deforestation on the environment and ultimately on human's life. Gabriel et al. (#5) present SMART ("Smart Monitoring and Reporting Tool"), an open-source digital tool aiming at supporting and facilitating patrolling and law enforcement in forests and other biodiversity hotspots. As of 2018, SMART is used in 765 protected areas in more than 60 countries, of which 400 protected areas located in 18 countries of the Asia-Pacific region.

Lee (#6) shows, based on a pilot study conducted in Tum Phai Thai National Park, in Northern Thailand, how unmanned aerial vehicles (UAVs or drones), as well as imaging technologies and algorithms can help collecting and analysing data in a rapid and cost-effective way, thus enabling stakeholders to assess initial degradation levels, develop restoration plans, and monitor restoration progresses. Saputra et al. (#7) develop a model, based on UAV data, estimating tree height, canopy cover, and tree diameter for teak trees of varied age classes (AC) in the Ciamis Forest Management Unit, West Java, Indonesia. Kamran et al. (#8), considering the importance of flying insects as pollinators or feed for higher trophic levels, as well as the dramatic decline of insect populations around the world, show how static traps and sweep-net carrying drones can be used to catch and sample insect populations at different heights, and different times in the day, across various habitats, even with limited or difficult access.

Tamang and Sharma (#9), focusing on invasive alien plant species (IAPS) management in Nepal, assessed and compared intensive and extensive management practices, opening new pathways for sustainable IAPS management. Mandawali (#10) explore the complex social and cultural dynamics affecting the establishment and maintenance of community-based tree nurseries (CBTNs) in five villages of the Ramu-Markham Valley, in Papua New Guinea (PNG). Almoite and Togado (#11) advocate for a greater focus on native tree species in the "National Greening Program" to preserve the Philippines' very rich biodiversity. They suggest innovative ways to improve the production of native tree species seedlings in the Philippines' modernized and mechanized forest nurseries (MMFNs).

Gupta et al. (#12) show how innovations in microscopy techniques have enabled drastic advances in the science of wood anatomy. One of the major applications of wood micro-structural studies is to facilitate wood species identification, which can be used for instance: in wood species identification, to track illegal timber trade, as forensic evidence in criminal investigations, or for proper conservation or restoration of historical monuments and wooden artefacts. The authors also present macroscopic techniques for timber identification. Ramatia et al. (#13) review two self-bonding mechanisms used to produce binderless particleboards - an alternative to conventional wood-based particleboards, with synthetic adhesives - that preserve human health and the environment. They also analyze the potential of non-wood lignocellulosic materials, including kenaf, oil palm, and bamboo, as raw materials for particleboard production.

These papers provide valuable insights to many issues to be covered in the roadmap, feeding, in particular, in the debates around the three following structuring issues:

- How can innovative technologies improve and facilitate monitoring and reporting? (See papers: #8, #6, #7, #4, #3, #5)
- How can innovative technologies strengthen the engagement of civil society, local communities, small-scale actors and youth in forest monitoring and management? (See papers: #2, #1, #10)
- How can innovative technologies support the optimization of processes and products for sustainable forestry and sustainable forest management? (See papers: #11, #9, #12, #13)

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How to effectively engage youth in satellite-based tropical forest monitoring?

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Abstract

Major advances in space technologies and their practical uses over the past three decades have made monitoring forest changes more accurate, steady, transparent, and inclusive. Open access platforms with high-quality data such as Global Forest Watch can help the public hold governments and companies accountable for how their management impacts forests. They can support all stakeholders in making smarter decisions regarding how to safeguard, maintain, and restore forests. Among these stakeholders are youth, who make up a large proportion of the population in tropical countries, where deforestation hotspots are often found. The youth also represent future generations, who will be the forest managers of the future and are the most impacted by current forest management practices.

This study explores potential ways to make tropical forest monitoring more inclusive, effective, sustainable, and transparent by constructively involving youth in tropical countries. Building upon three case studies from Malaysia and Indonesia, it identifies some potential key successes and limiting factors, which could be useful in the development of a roadmap for the application of innovative forest technologies in the Asia-Pacific region.

This analysis suggests the importance of involving established institutions (e.g. universities and government offices) and providing the right incentives for the different target user groups (e.g. forest rangers, law enforcers, university students). Young people's affinity and familiarity with innovative technologies are key advantages in the adoption of new satellite technology. Further, training and capacity-building activities to hone the technical and soft skills of youth can catalyze the uptake and application of satellite-based technology in forest monitoring. This study also shows the importance of creating and facilitating networks and communities of practice, where intensive communication, social media campaign, good storytelling, and, occasionally, anonymity appear to play major roles.

Initial stakeholder mapping has also been crucial in the case studies examined. Further, our analysis indicates the need for flexible planning and rapid prototyping (i.e. ‘fail fast, fail small’) to address setbacks due to technical issues and external challenges. Engaging stakeholders in current times, characterized by significant uncertainties, rapid technological changes, and information overload might necessitate frequent adjustments in the strategy. The Asia-Pacific roadmap shall take all of these factors into consideration.

Keywords: *tropical forest monitoring, remote sensing, youth, inclusivity, transparency*

Introduction

Major advances in space technologies and their practical uses over the past three decades have made monitoring forest changes more accurate, steady, transparent, and inclusive. The recent decision by the Norwegian International Climate and Forest Initiative (NICFI) to provide universal access to high-resolution satellite data of land cover and land-use in the tropics provides stakeholders with valuable opportunities to enhance forest monitoring activities and efforts to preserve tropical forests (NICFI 2020).

Tropical forests are powerful assets in climate change mitigation. According to Gibbs et al. (2018), roughly 8 percent of global greenhouse gases (GHG) emissions originate from tree cover loss in tropical forests, but they can provide 23 percent of the cost-effective climate mitigation needed before 2030. At the same time, many tropical rainforest countries are also developing countries with large youth populations. For example, Indonesia, one of the world’s deforestation hotspots, hosting about a tenth of the world’s remaining tropical rainforests, is home to more than 63 million young people under the age of 30, or almost a quarter of the country’s population (World Bank 2021). Solving the issue of deforestation clearly requires active youth participation, not least because they will be greatly impacted by existing approaches to forest and land management.

Youth in tropical countries can be a positive force for rainforest protection and climate change mitigation provided that they are

given the knowledge, opportunities and tools to act. Satellite-based tropical forest monitoring can provide such opportunities. State-of-the art space technology combined with open access platforms can help the public, including the youth, hold relevant forest and land use actors to account.

This study reviews three satellite-based forest monitoring initiatives from Indonesia and Malaysia, with a particular focus on youth, to study their key enabling and limiting factors. Through literature study and interviews with six individuals involved in the initiatives, it explores potential options to make tropical forest monitoring more inclusive, effective, sustainable, and transparent by constructively involving youth in tropical countries.

Satellite-based forest monitoring initiatives in Indonesia and Malaysia, with a particular focus on youth

This study focuses on the use of satellite technology for tropical forest monitoring, analyzing the application of this innovation in specific contexts, based on three case studies from Indonesia and Malaysia, with a focus on youth. The case studies illustrate various activities associated with satellite technology, which include data collection, analysis, management, interpretation and application. Different types of actors are involved depending on the scale, scope and objectives of the activity.

The first and second case studies illustrate the use of remote sensing tools (satellites and drones) and open access platforms such as Global Forest Watch (GFW), Google Earth and

Planet to visualize and monitor forest cover and detect deforestation. They describe how young people utilized these tools to empower communities to participate in forest monitoring and governance and devise strategic actions to protect tropical forest ecosystems. The third case study illustrates citizen science campaigns in data collection. The crowdsourcing campaigns mobilized an extensive youth network allowing a vast collection of data to develop more accurate land cover maps in Indonesia.

Case study 1. HAKA: Leveraging mapping tools, empowering stakeholders

HAKA¹ (Hutan, Alam dan Lingkungan Aceh; Forest, Nature and Environment of Aceh) is a grassroots non-profit organization dedicated to the protection, conservation and restoration of the Leuser Ecosystem in Aceh, the westernmost province of Indonesia. The Leuser Ecosystem comprises over 2.6 million ha of diverse landscapes including lowland rainforests, peat swamps, montane and coastal forests and alpine meadows. This unique natural asset is under immense threat from illegal logging, encroachment, infrastructure development and oil palm expansion (Sloan et al. 2018). HAKA works closely with the Leuser Conservation Forum (FKL),² government agencies, local organizations and communities to monitor and halt illegal deforestation, prevent poaching and mitigate wildlife-human conflicts in the Leuser Ecosystem.

Founded by a team of young Acehnese activists, born mostly in the late 1980s and early 1990s, HAKA is the leading force on deforestation monitoring in the Leuser Ecosystem. HAKA uses open access platforms such as GFW, Google Earth, and Planet extensively in routine monitoring work

and complements satellite observations with ground monitoring and checking. HAKA's geographic information system (GIS) team utilizes Google mapping tools³ to visualize forest cover data and detect deforestation (HAKA 2021a). To accelerate the monitoring exercises, the team takes advantage of near-real-time monitoring systems available in the GFW platform. In the field, HAKA has started to use the Forest Watcher mobile app,⁴ which allows the offline use of GFW and data recording (Bourgault 2018). Recently, HAKA's monitoring has been supported with drone-based aerial surveillance (Global Conservation 2020).

In Indonesia, law enforcement on deforestation often relies on field reports from civil society organizations (CSOs) and the public. The use of near-real-time satellite data by HAKA allows this approach to be conducted more efficiently. HAKA analyzes information from GFW's GLAD⁵ Alert (a weekly deforestation alert) and Forest Watcher and shares it with law enforcers and FKL, leading to more rapid, targeted patrols by the forest rangers, FKL members, and HAKA staff (Bourgault 2018; Purnamasari 2018). Additionally, FKL and HAKA collate their ground-checking and remote sensing data, publicizing it every year in the provincial capital and using it to instigate policy change and raise awareness. Their work has also been documented and disseminated widely via Google Earth Voyager⁶ (see **Figure 1**) (HAKA 2021a).

1 See: <https://www.haka.or.id/>

2 See: <https://leuserconservancy.or.id/>. FKL is an Aceh-based non-profit organization that aims to conserve and protect the Leuser Ecosystem. FKL works with local communities and government institutions to implement its programs (e.g., Wildlife Protection rangers and community-based restoration programs).

3 Such as: Google Earth Pro and Google Earth Web (see: <https://www.google.com/earth/versions/>); Google My Maps, (see: <https://www.google.com/maps/about/mymaps/>) and Google Earth Engine (see: <https://earthengine.google.com/>).

4 See: <https://forestwatcher.globalforestwatch.org/>

5 GLAD (Global Land Analysis & Discovery) Alerts, developed by the GLAD lab at the University of Maryland, identify areas of recent tree cover loss with a 30-meter resolution. See: <https://glad.umd.edu/>

6 See: <https://www.google.com/earth/education/explore-earth/>

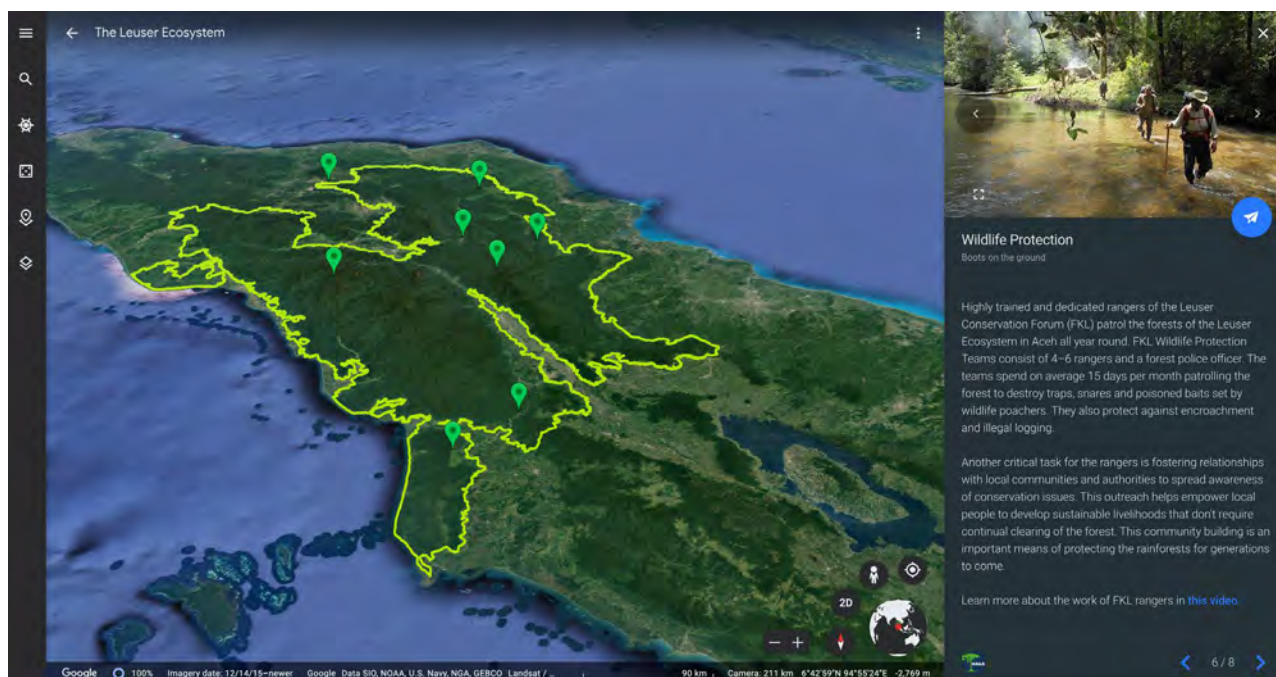


Figure 1: A snapshot of Google Earth Voyager⁷ shows an initiative (wildlife protection) by FKL and HAKA in the Leuser Ecosystem. A map of Leuser Ecosystem is provided in this platform (left image). Users can virtually visit the Leuser Ecosystem and learn about key initiatives to protect and conserve this ecosystem.

Source: Google Earth Voyager

To improve the capability of law enforcement officials, HAKA GIS staff have trained police officers and staff members of several forest management units, the conservation unit, and the national park management unit with the financial and technical support of the World Resources Institute (WRI)'s Global Forest Watch. As a result of HAKA's training program⁸ and intensive communication with government officials, GFW and its derivative products have been adopted by the local government and the forest management units as part of their forest monitoring systems (Bourgault 2018; Purnamasari 2018). The evidence-based report from the civil society is acknowledged and accepted for further action by the government agencies in the Leuser Ecosystem. To complement these

efforts, HAKA has also conducted other types of training targeting different stakeholders, such as raising awareness for local women and citizen journalism training for local communities (HAKA 2021b).

Their success stories include a crackdown on illegal gold mining and marijuana plantation in the forest zone by the police, and the use of GFW's fire hotspots data as a key reference to support the firefighting efforts of the government and local people (Bourgault 2018). The use of technology, combined with the enabling of government officials, local communities, and other relevant stakeholders with effective tools, as well as the mobilization of local, national and global campaigns, are HAKA and FKL's recipes to help reduce deforestation and improve forest governance in Aceh (Global Conservation 2020). However, challenges remain in ensuring that their efforts are sufficiently followed up by those of other actors. There have been reports of illegal actors resuming their operations after the crackdown periods.

⁷ See: <http://g.co/earth/leuser>

⁸ More recently, HAKA had conducted training on the use of GFW to journalists upon their requests. See <https://www.acehimage.com/belasan-jurnalists-ikut-pelatihan-jurnalistik-gfw/index.html> (in Indonesian).

Case study 2. Hutanwatch: Who Watches the Watchmen?

Hutanwatch⁹ is an open data website that promotes forest transparency in Malaysia. The platform combines user-contributed information, datasets from GFW, and tools to monitor forest cover changes and investigate forest loss. Hutanwatch was launched by a group of young environmental professionals in response to the lack of consolidated maps of forest areas in Malaysia and limited access to such information (Barad and Jamilla 2019). Information on forest and land use in Malaysia is scattered across different agencies, depositories and databases, which hinder transparency, independent monitoring and public participation in forest management (Law 2020).

Hutanwatch collates and curates spatial data provided by various users and integrates this data into customized map applications using GFW MapBuilder.¹⁰ The spatial data are visualized using the GFW platform and categorized into multiple interactive maps covering Peninsular Malaysia (see **Figure 2**), Sarawak and Sabah, as well as parliamentary constituencies. The analysis tools, adopted from GFW, enable users to select the area of interest and analyze forest cover changes. On top of GFW key features such as tree cover loss or gain, GLAD alerts and active fire watch, Hutanwatch provides additional maps

of Permanent Reserve Forests (PRF)¹¹, Totally Protected Areas and critical landscapes legally designated by Malaysian government. These maps are either contributed by various users or obtained through the digitization of maps and land boundaries from official government reports and documents. The availability of these additional data layers is a critical first step in identifying land boundaries and ownership (Barad and Jamilla 2019; Law 2020). In Malaysia, forestland is categorized as permanent reserved forests (PRF), state-land forests, national parks, and wildlife reserves. Each forest category is managed by separate state and federal government agencies. In the case of deforestation (illegal or otherwise), the responsible agency must be identified before further action is taken.

The free and open access to data now creates a level playing field for all individuals and organizations working in the field on forest monitoring, advocacy and stewardship in Malaysia (Law 2020). Access to this information was previously restricted to government agencies, selected research institutions and consultancy firms. Using Hutanwatch, any interested party can investigate forest cover change, check whether tree loss occurs within or outside forest reserve boundaries, identify potentially illicit forest activities and encourage additional courses of action – for example, by informing Hutanwatch, journalists, local representatives, CSOs or enforcement agencies. The information transmitted to Hutanwatch is validated by cross-checking it with satellite images from the Planet platform, tree cover loss history from GFW and relevant environmental impact assessment

9 “Hutan” means forest in both the Malaysian and Indonesian languages. See: <https://www.hutanwatch.com/>

10 GFW MapBuilder is a tool to create and customize a forest monitoring application. It enables users to combine their own datasets with GFW’s cutting-edge data and analysis tools. Applications can be deployed as standalone websites, embedded into existing websites or shared using integrated social media tools. See: <https://www.globalforestwatch.org/mapbuilder/>

11 The Malaysian National Forestry Act (Act 313, 1984) allows the relevant State Authority to declare, by notification in the Gazette, any area as “Permanent Reserved Forest (PRF)”. This Act defines PRF as “any land constituted or deemed to have been constituted a permanent forest reserve under this Act”. See: https://www.forestry.gov.my/images/JPSM/wargaperhutanan/AktaAPN_en.pdf

The status of PRF of a given area is not linked to its current land cover. An area legally designated as PRF may have temporarily lost its forest cover. Conversely, some forested areas are not legally designated as PRF, as in the case of the Taman Negara/National Park (Hamid and Abd Rahman 2016).

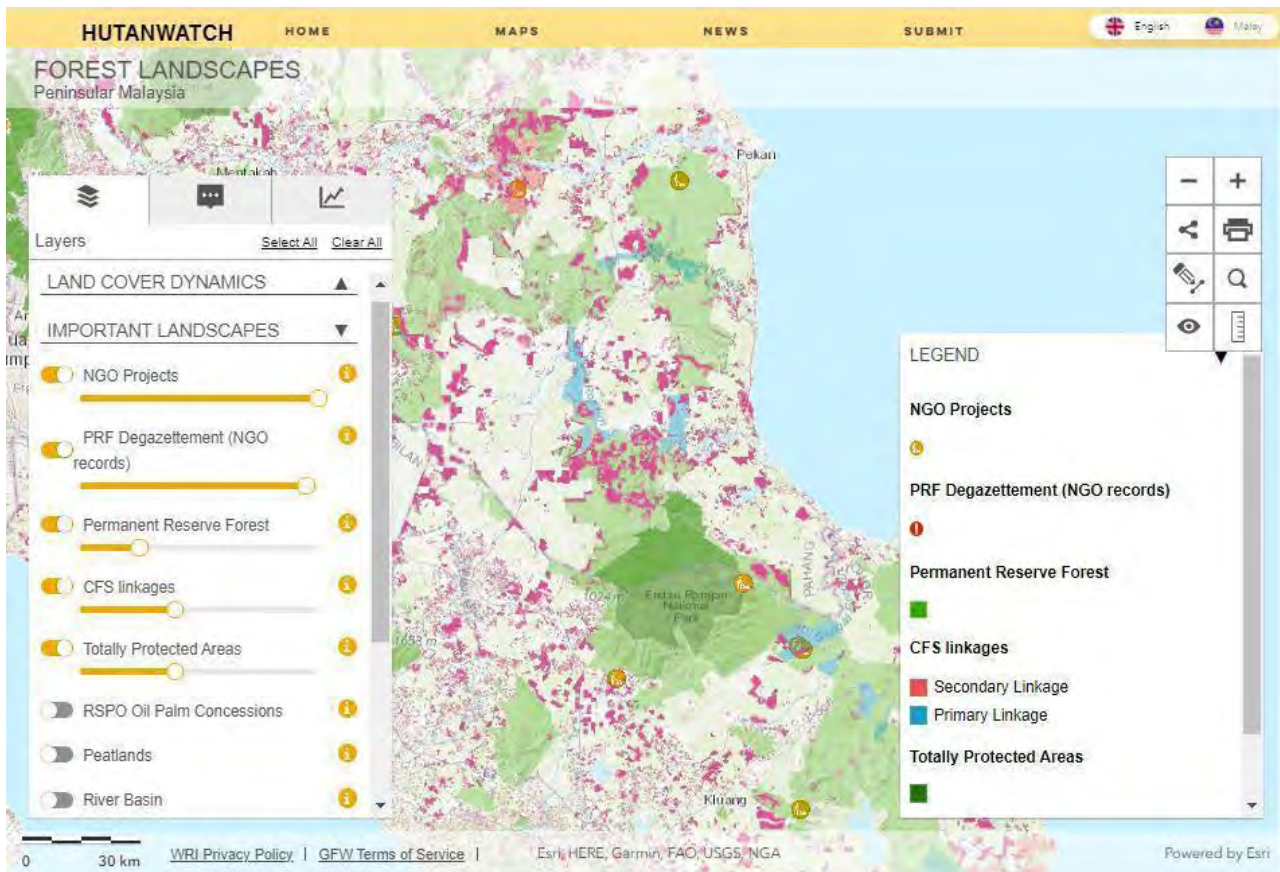


Figure 2: A snapshot of Hutanwatch shows an interactive map of Peninsular Malaysia. Additional features of important landscapes (NGO projects, PRF Degazettement,¹³ Permanent Reserve Forests, CFS¹⁴ linkages and Totally Protected Areas) correspond to user-contributed data. Hutanwatch’s disclaimer states that data may not reflect current/official land use classification. In this map, pink areas represent tree-cover loss over 2015–2018 (accessed through GFW).

Source: Hutanwatch.com

(EIA) reports, and also reports published by government agencies. Next, the validated information is uploaded to Hutanwatch’s News page,¹² where the public can read and add further information on the incidents. As a storytelling tool, Hutanwatch empowers its users to substantiate their claims on suspicious or potentially illicit forest changes and activities with evidence from satellite observations. Users can make use of the information available in Hutanwatch, frame the issue in the context of local landscape and instigate public discussion. The news stories published in Hutanwatch platform are sometimes widely shared through social

media, spark media pressure and lead to public outcry (Barad and Jamilla 2019).

In addition to facilitating public participation and inclusiveness in forest management, the tools and features of Hutanwatch can be used to hold authorities accountable. For instance, Hutanwatch published a news article about the ‘quiet excision’ (i.e. degazettement) of a 6,000-ha Permanent Forest Reserve

¹³ Degazettement is defined as a loss of legal protection for an entire national park or other protected area.

¹⁴ The Central Forest Spine (CFS) of Peninsular Malaysia, composed of four main forest complexes, is an important natural landscape of Malaysia, providing 90 percent of the population’s water supply and harboring the remaining population of Malayan tigers in its forests.

¹² See: <https://www.hutanwatch.com/news>

in Endau-Rompin National Park.¹⁵ Upon receiving tip-offs and evidence from its users, Hutanwatch validated the submission with satellite images from the Planet platform and tree cover loss history from GFW. Using these data, Hutanwatch alleged that the pristine 6,000-ha forest reserve was deliberately classified as ‘degraded forest’ to open the way for clear felling for conversion to agricultural and industrial land-uses. The state’s Forestry Department responded, stating that “the area where logging has been approved is on government land outside the buffer zone,” and covers only about 3,800 ha. They also said that the maps referred to by Hutanwatch were inaccurate and that they would upload the most updated ones on the Department’s website (The Star 2019). No further action was taken by the Department.

Hutanwatch, being a platform for sharing potentially high-risk or confidential sources, remains anonymous. The identity of the team behind Hutanwatch is undisclosed to protect them from potential litigation by various agencies for breaching data, or in the worst-case scenario, from threat and intimidation by illicit parties. Likewise, the identities of contributors (including whistleblowers) are kept anonymous. The anonymity of Hutanwatch creates a set of challenges. Not only is data obtained from Hutanwatch heavily scrutinized, but the legitimacy of Hutanwatch as a credible source is also questioned and sometimes disregarded by official agencies.

Case study 3. Urundata: Sumbang Data Jadi Nyata (Contribute data, make it concrete)

Urundata¹⁶ is a project to collect data through public participation (i.e. crowdsourcing). It was developed by the RESTORE+ consortium,¹⁷ which consists of the International Institute for Applied Systems Analysis (IIASA), World

Agroforestry Center (ICRAF), WRI Indonesia, and World Wildlife Fund (WWF) Indonesia. RESTORE+ aims to strengthen participatory and evidence-based land use policymaking via citizen science campaigns to inform forest and landscape restoration strategies in Indonesia. This is done through the development of a mobile application, freely available on Google Play Store, that allows the public, especially youth, to participate in data collection campaigns revolving around interpreting and verifying land cover and land use data obtained from satellite images (RESTORE+ 2019; Suwastoyo 2020).

The Urundata app currently consists of two ‘games.’ The first game, *Pilahpilih* (based on IIASA’s *Picture Pile*), allows users to compete with each other in interpreting land cover satellite images displayed by the app (see **Figure 3**). The conventional process of interpreting satellite imagery generally involves a limited number of experts, making it a time-consuming and costly process, but the interpretation can be made more efficient and cost-effective with the participation of the public via the Urundata app (RESTORE+ 2019). Crowdsourced information is used as reference or training data for a machine learning-based mapping product, facilitating and accelerating supervised land classification. To ensure data quality, control images previously validated and interpreted by experts were randomly shown in the app (see **Figure 3**). Users are informed whether they have correctly or incorrectly interpreted the control images and given a bonus score or penalty accordingly. Further, crowdsourced data are filtered based on the estimated accuracy of each contributor (RESTORE+ 2020). The consortium has specifically targeted students from more than 10 local universities in South Sumatra and East Kalimantan and formed partnerships with these universities and government bodies to facilitate data collection via the app (Suwastoyo 2020; Savitri 2020). Additional crowdsourcing activities were also conducted involving trained GIS experts from research institutions and government agencies, and the results were used to perform accuracy assessments on the maps produced by machine learning algorithms (RESTORE+ 2020).

15 See: <https://www.hutanwatch.com/single-post/2019/04/01/Taman-Negeri-Endau-Rompin-A-Quiet-6000-ha-Excision>

16 See: <https://urundata.id/beranda> (in Indonesian language)

17 For more information on this consortium, see: <http://www.restoreplus.org/>

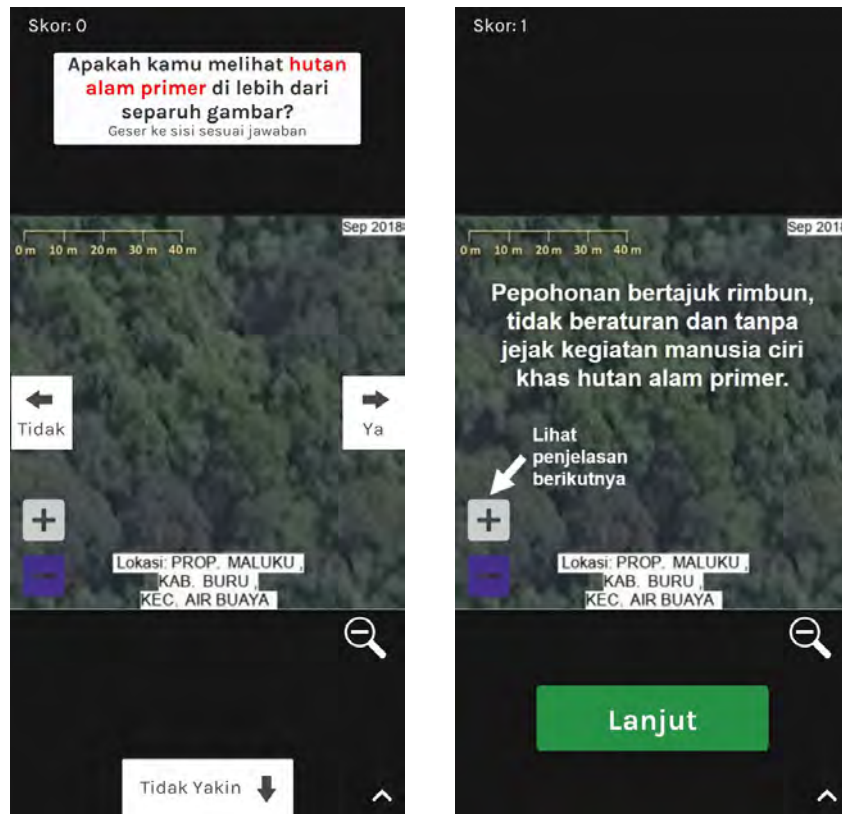


Figure 3: Screenshots of Pilahpilih. In the image on the left, participants are asked whether they see primary forest in more than half of the image. They can swipe left if they think the answer is ‘no’, swipe right for ‘yes’, or swipe down if they are unsure. As this is one of the control images previously validated by experts, participants are informed of the right answer and the explanation (the image on the right).

Source: Urundata App

Inspired by the popular Pokemon Go game (Taylor 2020), the second game, Jelantara, requests users to visit specific locations and ask them information related to land cover and evidence of land degradation. To overcome connectivity issues in the field, the RESTORE+ team has made it possible for users to collect information offline and upload it when they have internet access. The RESTORE+ team initially listed university students as the primary target users for Jelantara. Subsequently, the primary users were expanded to include village-based extension service officers in South Sumatra and East Kalimantan.

This has led to the collection of millions of data inputs given by more than 1,000 participants (Savitri 2020). As of April 2021, there are 1,058 contributors and 4,410,415 observations collected through 21 Urundata

campaigns.¹⁸ These crowdsourced data, collected through Pilahpilih and Jelantara, are used to develop more accurate land cover and land degradation maps in South Sumatra and East Kalimantan, the two pilot provinces for RESTORE+. These results will be used to help develop a portfolio of sustainable restoration options. As the project emphasizes data transparency, the team plans to provide open access to these crowdsourced data (in a geospatial format) on their website, so that the public can explore and process them further.

The Urundata approach appears to have generated plenty of interest from its existing target users (university students and extension service officers), many of which are young and technologically savvy

¹⁸ The figures were obtained from Urundata’s homepage. See: <https://urundata.id/>

(Savitri 2020). Interviews with RESTORE+ team members suggest that some users seem to be attracted by the incentives proposed (i.e. internships with one of the consortium members and online shopping vouchers), though many are attracted simply because the games are fun, impactful, and educational. The establishment of a direct line of communication between users and the RESTORE+ team members via WhatsApp groups enabled the team to quickly solve the many technical issues encountered and improve the Urundata platform and overall approach over time. While the Urundata app is currently used to support RESTORE+ objectives, the team hopes that it can be turned into a nationally-owned, collaborative data collection platform for various purposes in the future.

Analysis of enabling factors and constraints for effective adoption of satellite-based monitoring approaches among youth

The three case studies demonstrated the successful adoption of satellite technology in forest monitoring, advocacy and stewardship in diverse contexts. This section analyzes the enabling factors and associated constraints that contribute to the effective adoption of satellite monitoring, focusing on youth. The enabling factors and constraints are summarized in **Table 1** and discussed.

Enabling factors for effective adoption of satellite-based monitoring

Stakeholder mapping, identification and engagement

Identifying and engaging relevant stakeholders is key to the successful adoption and deployment of innovations. First, target user groups must be identified according to their needs, interests, influence and impact. Then, the innovation must be tailored to match the profile (skills, interests and needs) of the target groups. In our case studies, satellite-based innovative monitoring approaches attract youth and

match their affinity and familiarity with the latest technology. Through free access and some repackaging, data providers (e.g., GFW, RESTORE+, Google) can facilitate youth access to and use of satellite-monitoring data. Urundata citizen science campaigns target young university students and enrich its participatory monitoring approach, with the fun element of gamification and intensive use of social media (RESTORE+ 2019; Suwastoyo 2020). The use of satellite monitoring allows HAKA and Hutanwatch users to bypass certain resource-intensive steps in land and forest monitoring and shifts their resources to effective action to advocate, restore, conserve and protect the forests (Purnamasari 2018). In the case of Hutanwatch, there is pressing demand from CSOs, environmental practitioners and the general public for free, open access and consolidated maps of forest areas in Malaysia, which led to the creation of the Hutanwatch platform (Barad and Jamilla 2019; Law 2020). The team decided to keep the Hutanwatch platform anonymous upon considering safety and legal concerns and to stay independent and non-partisan.

Relevant skills and capacity building

Young people can be empowered to interpret, integrate and manage the huge amount of satellite information by receiving further training in spatially referenced data (GIS), mapping, software operation, information technology, statistics and algorithms. The technical staff behind HAKA and Urundata received formal training in geography or information technology at university or work.¹⁹ Varying degrees of expertise are required depending on the scope and scale of satellite monitoring application. Nevertheless, basic mapping and spatial analysis tools can be mastered in a relatively short time. In Urundata apps, the game starts with a basic introduction to satellite imagery interpretation. Hutanwatch was developed by building upon the wealth of resources available online for independent learning²⁰ (Barad and Jamilla 2019).

19 Two of HAKA's senior GIS staff/trainers have even been trained at the WRI and Google headquarters in the United States of America.

20 e.g. GFW Help Center (see: <https://www.globalforestwatch.org/help/>); and GFW MapBuilder (see: <https://www.globalforestwatch.org/mapbuilder/>)

Table 1: A summary of the main objectives, target users, enabling factors and constraints for effective adoption of satellite technology for the three case studies.

Case study	HAKA	Hutanwatch	Urundata
Main objectives	1. Monitor illegal deforestation, visualize forest cover data 2. Use near-real-time satellite data for more rapid, targeted patrols	1. Provide information on forest cover changes and forest loss to the public 2. Share and validate data on forest cover changes	1. Interpret and verify land cover data from satellites in a time-efficient manner 2. Develop more accurate land cover and land degradation maps
Target users	Forest rangers, HAKA and FKL staff, law enforcers	General public, environmental practitioners	University students
Enabling factors:			
Stakeholder mapping	Target user groups are identified and delivery of technology is tailored to their profile (skills, interests, and needs)		
Skills	The core staff are experts or have experience with GIS, mapping and software		
Capacity building	HAKA team trains CSOs, officers, journalists	Users train their colleagues, students to use Hutanwatch	Urundata routinely runs seminars and workshops
Communities of practices	Close collaboration across multiple stakeholders	Virtual community based on user contributions	Extensive community of university students, and experts
Rapid prototyping	Improvement of Forest Watcher app based on user experience	Hutanwatch continues adding new features on its platform	Continuous feedback from users to improvise Pilahpilih and Jelantara apps
Constraints:			
Technical limitations	Limited internet connectivity, leading to issues accessing app	Inexperienced users struggle to use the platform	Technical glitches due to limited bandwidth
External challenges	More manpower needed to cover larger areas	Lack of new submissions due to pandemic restriction	Road inaccessibility reduces data collection/coverage
Data interpretation	Contested definitions, methodology and results	Hutanwatch's data validity can be questioned	More government experts needed to validate data

Soft skills such as communication, human behavior and social skills are equally important for effective adoption of satellite-based monitoring technology. This is particularly evident in Urundata campaigns that mobilize the crowd to collect relevant data for land cover analysis. To reach out to a huge number of participants, the objectives and methodology of Urundata are distilled

and communicated clearly via intensive social media campaigns (RESTORE+ 2019). Urundata campaigns designed appealing slogans to attract youth.²¹ Experts in social sciences could improve the implementation and impact

21 Such as: 'Data Warrior [Pahlawan Data]' and 'Together, the #DataWarrior make a difference for Indonesia! [Bersama-sama, para #PahlawanData membawa perubahan untuk Indonesia]'

of the campaign in the future by providing recommendations based on the analysis of contributors' characteristics, motivations, behaviors and social interactions.

The widespread uptake and application of satellite monitoring technology necessitates training and capacity building for users. Knowledge transfer and technical upskilling of local organizations can empower them to operate the technology independently, thus ensuring the sustained use and maintenance of resources allocated to adopting the technology. Often, local organizations have limited or already stretched human resources, competing priorities and limited facilities to accommodate new technology. With funding and technical assistance from GFW and WRI Indonesia, HAKA is able to provide training tools for law enforcers and journalists. In addition, as a member of the Google Earth Outreach Trainer Network,²² the HAKA team offers trainings to other CSOs or institutions in need (HAKA 2021a). Similarly, the training component (seminars, workshops, and roadshows) is integral to Urundata campaigns. Conversely, Hutanwatch does not offer direct training to users. Hutanwatch savvy users from research, academia and CSOs introduce this platform to their network and take the initiative to train their students/colleagues. Since Hutanwatch is a customized version of GFW, Hutanwatch users can also rely on the technical support offered by the GFW Help Center.

Communities of practices

Communities of practices created around satellite-based monitoring approaches could synergize and strengthen the efforts of individuals and organizations to generate transformative societal changes. Community size matters: the large Urundata user community has enabled the RESTORE+ team to address analytical and statistical challenges in satellite data analysis and interpretation (Wijaya 2019; Savitri 2020). Collaborative efforts by HAKA, the Leuser Conservation Forum, government agencies, local

organizations and communities are critical to conserving and protecting the Leuser ecosystem (Purnamasari 2018). In both cases, a sense of community is built on the vision of greater transparency, active participation, efficient data acquisition and analysis, and more accurate mapping. Moreover, the community is strengthened by formal partnerships and the sharing of human and financial resources among key stakeholders.

In the case of Hutanwatch, a virtual, online community centered on user contribution is built via the sharing and exchange of information and datasets. Hutanwatch's vision of promoting forest transparency in Malaysia serves as the unifying factor for users from diverse backgrounds to share their data, gradually improving and adding value to the platform (Barad and Jamilla 2019). More importantly, the identities of contributors are kept anonymous, creating a safe and confidential space for sharing sensitive or classified information. Hutanwatch's role as whistleblower requires neutrality, thus there is no apparent need to collaborate with other organizations. Nevertheless, there is tremendous potential benefit in mainstreaming Hutanwatch to youth in academic institutions, as illustrated by the success of Urundata. Collaboration and data sharing with official institutions could also improve the accuracy of satellite data analysis and interpretation (e.g. Hamid and Abd Rahman 2016; Mohd Najib and Kanniah 2019).

Rapid prototyping

A rapid prototyping approach involves faster design, development, execution, evaluation and improvement cycles (i.e. 'fail fast, fail small') (Huang et al. 2010). It provides opportunities to improve the initial concept and identify its strengths and weaknesses, as well as possible future developments in an efficient manner. Starting from a simple map, Hutanwatch evolves and continuously adds new features on its platform²³ (Barad and Jamilla 2019). The lessons learned on deforestation monitoring by HAKA and FKL in

22 See: <https://www.google.com/earth/outreach/become-a-trainer/>

23 e.g. news page, data submission tool and multiple thematic maps integrating user-submitted data.

Aceh have been useful for the GFW team in the gradual development of Forest Watcher (Payne and Barrett 2017). For a long time, HAKA and FKL teams had to rely on their GPS devices, cameras, and paper forms when conducting patrols. The Forest Watcher mobile app now brings the dynamic online forest monitoring and alert systems of GFW offline into the field (Purnamasari 2018). The GFW team in Washington, DC is relying on Forest Watcher's on-the-ground testing to rectify any issues. Similarly, the RESTORE+ team is actively seeking feedback from Pilahpilih and Jelantara users through various channels (e.g., WhatsApp and emails) to continuously improve user experience. They also started small by first targeting a small number of users, monitoring progress, and modifying features accordingly before moving on to a larger number of users (RESTORE+ 2019). Such an iterative process is observed in all three case studies.

Constraints to the effective adoption of satellite-based monitoring

Technical limitations

Various technical limitations could hinder the realization of the innovation's maximum potential in all three case studies. Technical glitches such as limited internet access and unstable connections can make it difficult to access the GFW website and download the app. Similarly, low internet connectivity slows down the process of uploading data to Pilahpilih and Jelantara app. During earlier campaigns, the Pilahpilih app often crashed due to bandwidth issues. Users persistently sent notifications via WhatsApp to the RESTORE+ team to verify whether their data had been submitted successfully. A lack of experience or expertise in using map applications like Hutanwatch and the GFW platform might also deter new users from utilizing these freely available tools. As mentioned in earlier sections, training, capacity building and community of practices could facilitate greater adoption of satellite monitoring technology by a broader user base.

External challenges

In all case studies, satellite monitoring data is complemented with ground-truthing, which is associated with a different set of challenges. A key challenge faced by the players of the Jelantara app is restricted access to certain locations due to road inaccessibility or restrictions by landowners. Consequently, no data is collected for these no-go areas, thus reducing the coverage of validation points. During the COVID-19 pandemic, the lack of new submissions to Hutanwatch may be explained by travel and movement restrictions imposed by the Malaysian government. Hutanwatch relies on the submission of information and data by contributors, and many data gathering activities have been restricted during the pandemic. Similarly, the pandemic has also led to reduced reporting of illegal deforestation in Aceh, especially reporting by independent CSOs (HAKA 2021b). To circumvent this issue, HAKA has intensified trainings for citizens, including women, to maintain the momentum of environmental campaigns and advocacy in Aceh. This is also important because of the large size of the Leuser ecosystem, which needs constant monitoring. More people are needed to support law enforcement efforts.

Data interpretation

Advances in satellite technology continue to provide high-resolution data in massive quantities, which are coupled with advances in data processing and analysis. Most importantly, the data obtained from satellite technology needs to be appropriately validated and interpreted to ensure the accurate representation of what is being measured (e.g. forest or tree cover loss, level of degradation). For instance, the key data outputs from GFW are tree cover change

and loss.²⁴ In many jurisdictions, tree cover loss may not always signify deforestation.²⁵ In Aceh, while law enforcement officials have widely adopted GFW in their work to fight illegal deforestation and forest fires and acknowledged the efficacy of GFW data²⁶ (Bourgault 2018, ACEHKINI 2020), the Ministry of Environment and Forestry of Indonesia often questions GFW's definitions, methodology, and results (Siti Nurbaya 2021). This could potentially undermine the use of GFW by Aceh's officials, as the Ministry plays a role in the management of Aceh's forests. In a broader context, government agencies around the world may also disagree with the GFW approach and opt to ignore GFW data and observations.

Moreover, the lack of contribution and participation by official institutions, which hold significant records of high-quality data (maps, satellite data at multiple resolutions, ground-truthed data,²⁷ etc.), can reduce data quality and interpretation. The RESTORE+ team has had relatively limited participation from the Jakarta-based Ministry of Environment and Forestry during the expert crowdsourcing stage. The Ministry's staff members are key experts and serve as one of the authorities in developing official land cover maps in Indonesia. Greater interaction with the Ministry's relevant staff could have boosted Urundata's technical credibility and policy relevance. Similarly, Hutanwatch also depends on the availability of high-quality, accurate maps and data from contributors,

including government agencies. As an open data tool, the quality of submissions to Hutanwatch varies, and their validity can therefore be questioned. However, this is expected as Hutanwatch aims to incite public discussion on specific deforestation cases²⁸ and to implore state governments to be more transparent by releasing official data to counteract inaccurate data or maps. One founder of Hutanwatch said: "If one person without any formal GIS or programming background built Hutanwatch, there's no reason why the government agencies can't develop something more sophisticated to remain accountable to the public." (Barad and Jamilla 2019).

Conclusion

Satellite-based forest monitoring initiatives, that have emerged as a response to alarming rates of tropical deforestation and forest degradation, present their own challenges. Based on a literature review and interviews, this study identified several enabling factors that can improve youth involvement in satellite-based forest monitoring (e.g. stakeholder mapping, technical and soft skills, capacity building, communities of practices, and rapid prototyping), as well as three major constraints to youth-linked satellite-based forest monitoring initiatives in Indonesia and Malaysia (e.g. technical limitations, external challenges and issues associated with data interpretation).

The three case studies demonstrated multiple ways to use satellite technology depending on the primary objectives (e.g. improving law enforcement, disseminating information for advocacy, or developing more accurate maps), the target user groups (e.g. forest rangers, law enforcers, or university students), and the beneficiaries (such as local communities, governments, and the general public). To facilitate greater adoption of satellite technology by the youth, funding and resources from various actors including governments, educational institutions, the

24 According to GFW-GLAD, tree cover is defined as all vegetation greater than 5 m in height and may take the form of natural forests or plantations across a range of canopy densities. Tree cover loss is defined as "stand replacement disturbance," or complete removal of the tree cover canopy at the Landsat pixel scale.

See <https://blog.globalforestwatch.org/data-and-research/a-guide-to-gfws-forest-change-data/> for more information on methodology used by GFW.

25 See, for instance, the Malaysian example in Hamid and Abd Rahman (2016).

26 As stated by the head police officer of Aceh, "The data released by this application [GFW] is considered as A1 information data (valid); there is no doubt of its validity by the officers carrying out the operation." (ACEHKINI 2020)

27 Ground-truthed data refers to remote-sensing data that has been validated by *in situ* observations

28 See example provided in Hutanwatch's section on 'A quiet excision of a 6,000-ha Permanent Forest Reserve in Endau-Rompin National Park' (Hutanwatch 2019).

private sector, and members of the public (via crowdfunding) can be allocated to activities that support the enabling factors identified above. Expanding the communities of practice and capacity-building activities beyond national borders could accelerate technology adoption at the regional level. Further, the next course of action could focus on addressing constraints. The issues with data interpretation are especially pertinent as they relate to data quality, credibility and policy relevance.

The following recommendations may be relevant to existing youth groups planning to expand their use of satellite technology:

- expand the user base beyond the pilot phase (e.g. rural youth in Urundata campaigns, indigenous communities in Hutanwatch and GFW),
- expand geographic coverage (e.g. Urundata could be expanded to cover other Indonesian provinces)
- strengthen participation and collaboration with established institutions to share data and expertise.

Importantly, stakeholder mapping and rapid prototyping are central to ensure that the approaches match the needs, interests, influence and impact of the potential user groups and beneficiaries during times of high uncertainty, rapid technological change, and information overload.

Overall, these three case studies show that when empowered with the right technologies and enabling factors, youth can be a positive force in monitoring and tackling tropical deforestation. Satellite technologies are a powerful tool that can be used by youth to strategize forest monitoring and patrolling, create platforms for active public participation, raise awareness among stakeholders and advocate for a more sustainable, transparent and inclusive forest management.

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Forest Watcher: Employing citizen science in forest management of Nepal

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Abstract

Nepal's deforestation rate is one of the highest in the world, at 25 percent over the past 20 years. In Nepal, community forest user groups (CFUGs) take care of natural resources and promote social inclusion. The success of a conservation program depends on the involvement of local people.

Forest Watcher is a mobile application that helps collect critical baseline data about forest status and strengthens community participation in forest conservation. It provides dynamic online forest monitoring and alert systems. Data can be stored in the mobile device when it is not connected to the internet. Hence, regardless of connectivity, frontline forest guardians and citizen scientists can quickly access Global Forest Watch (GFW) satellite-derived forest datasets to collect near-real-time tree cover loss, deforestation and fire alerts information in the field.

In collaboration with the relevant Divisional Forest Offices and Local Councils, we trained 68 elected CFUG members from 34 community forests across seven districts of western Nepal to use Forest Watcher. In total, 6,657 hectares of community forest were monitored and 2,983 Global Land Analysis and Discovery (GLAD) deforestation alerts were reported from March 2020 to December 2020. CO₂ emissions were the highest in Jumla as the district experienced the greatest tree cover loss (1,160 ha from 2001 to 2020). With Forest Watcher, even during the COVID-19 pandemic, local communities were able to patrol the forests at a safe distance and receive alerts at their fingertips. With mobile applications, data collection will become more efficient and accurate and delivered in real time, thereby reducing the risk of error. It will also be possible to authenticate data. Such data will facilitate the development of long-term effective conservation plans for forests and boost current conservation efforts.

Keywords: *Forest Watcher, Community Forest, Forest Guardians*

Introduction and background

Indigenous peoples and local communities are the forefront stewards of natural resources. Forests are best protected when local people have rights over their management (Petersen and Pinteá 2017). Their traditional knowledge complements scientific research and helps support conservation strategies, especially in remote mountain ecosystems where significant data gaps still exist. In the Rio Declaration on Environment and Development (United Nations 1992), the United Nations General Assembly proclaims that “environmental issues are best handled with the participation of all concerned citizens” (Principle 10).

According to GFW, Nepal lost 47,100 ha (471 kha) of tree cover between 2002 and 2020, including 3,800 ha (3.8 kha) of humid primary forest.¹ A number of factors are contributing to deforestation and forest degradation in Nepal, including habitat degradation, illegal harvesting, wildfires, agricultural expansion, and weak state control over the land (Chaudhary et al. 2016). Nepal’s deforestation rate is one of the highest in the world, at 25 percent over the past 20 years. To combat growing issues of deforestation and forest degradation, Nepal’s government has adopted a strategy centered on the 1976 National Forestry Plan, which promotes community participation in sustainable forest management and conservation (Springate-Baginski et al. 2003). In least developed countries like Nepal, the community-based forest management (CBFM) approach has so far been one of the most promising achievements in the green economy sector. Nepal continues to be a global leader in CBFM development (Ojha et al. 2007; Pathak et al. 2017). The approach has demonstrated success in its dual objectives of ecological restoration and sustainable livelihood enhancement. Under the CBFM framework, 1.8 million hectares of forest land has been handed over to 19,361 CFUGs, representing nearly 1.45 million households, or 35 percent of Nepal’s population (DoF 2015). Some research has shown that conservation efforts without community participation

often collapse, particularly in areas with high population density, resource sharing disputes, and highly fragile and smaller protected areas (Isager et al. 2001; Brofeldt et al. 2014).

Recent technological breakthroughs in remote sensing have allowed a qualitative leap in our understanding of forest ecosystems and management (Goetz and Dubayah 2011; Henry et al. 2015; Abad-Segura et al. 2020; FAO 2020). Remote sensing observation is emerging as an indispensable tool for tracking land cover changes and is gaining significant momentum in different aspects of applied ecology and conservation biology (Wang et al. 2010; Kumar 2011; Nagendra et al. 2013; Lawley et al. 2016). Conventional forest assessment methodologies include extensive field surveys, paper-based data collection and block/transect-based² analysis of forest stocks. Forest guardians (FGs) used to record data manually on datasheets, which resulted in a lot of errors. In addition, these conventional forest monitoring practices can limit the timely and precise analysis of survey data. Mobile applications have immediate benefits over conventional paper-based approaches: they allow FGs to record data much more easily and on site.

Description of the innovation

Study area

Within a latitudinal range of approximately 200 km, Nepal undergoes vast altitudinal changes, ranging from 60 m along the southern border up to 8,848m on Mount Everest in the north. This difference greatly impacts Nepal’s landscape and climate. The study area, illustrated in **Figure 1**, includes seven districts – Kalikot, Jumla, Jajarkot, Rolpa, Dolpa, Rukum West and Rukum East – situated in Western Nepal, and covers 18,644 km², including 6,079 km² of forests. This area connects three protected areas (PAs), namely: Rara National Park, Dhorpatan Hunting

1 See: <https://gfw.global/3rL8NHM> [accessed 30.05.21]

2 A forest block is a contiguous area of forest in any stage of succession and not currently developed for non-forest use. A transect is a path along which one counts and records occurrences of the objects of study (e.g. plants).

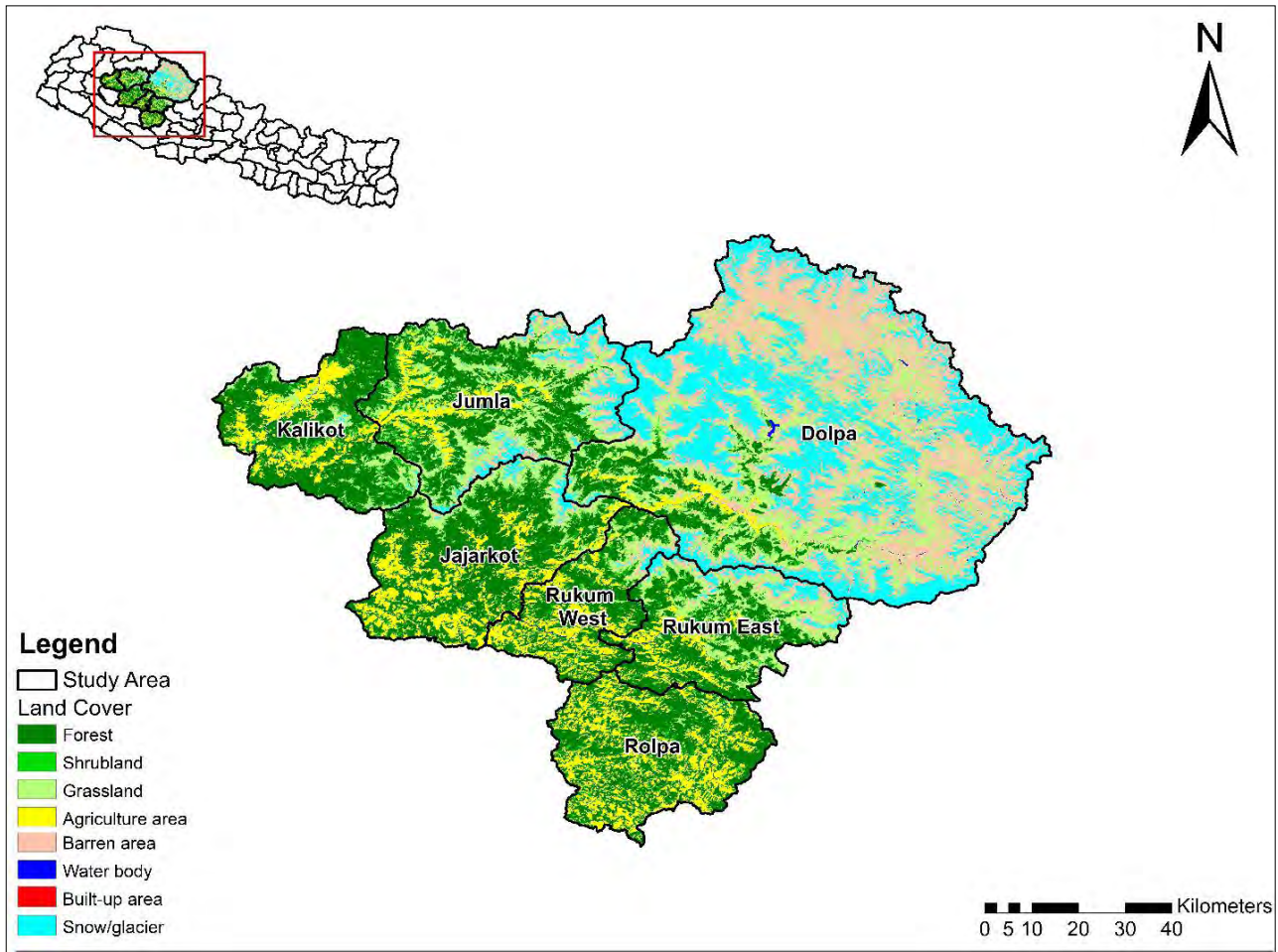


Figure 1: Study Area. Land Cover data taken from ICIMOD (2010).

Reserve, and Shey Phoksundo National Park. The study area mainly comprises Himalayan subtropical pine forests, subalpine conifer forests, broadleaf forests, alpine shrubs and meadows. Intact forests can be found only in Jumla and Jajarkot districts. Some areas have warm and temperate climate with dry winters and warm summers, whilst others have a polar tundra and snowy climate with dry winters and cool summers. The Kalikot district is the westernmost distribution edge (81.66° E) for some of the world's most endangered animals like the Himalayan Red Panda.

From 2001 to 2020, tree cover loss in the seven districts of the study area amounted to 4.63 kha.³ Over the 20-year period, there were substantial variations in tree cover loss, including a steep surge in 2017 (**Figure 2a**).

Figure 2b illustrates tree cover loss at the district level between 2001 and 2020. The greatest tree cover loss occurred in Jumla (1.12kha),⁴ followed by Kalikot (912 ha),⁵ Jajarkot (785 ha),⁶ Rukum East (537 ha),⁷ Dolpa (481 ha),⁸ Rukum West (423 ha)⁹ and Rolpa (375 ha).¹⁰

From 2001 to 2020, tree cover loss in the study area released 2.74 million metric tons (Mt) of CO₂e i.e. 2.09 Mt of CO₂ and 0.65 Mt of other greenhouse gases (GHGs), into

3 See: <https://gfw.global/3y2ICRN>

4 See: <https://gfw.global/2S6tiP7>

5 See: <https://gfw.global/3gaxlQz>

6 See: <https://gfw.global/3wRuaJG>

7 See: <https://gfw.global/3cfn0H4>

8 See: <https://gfw.global/3wVLgGo>

9 See: <https://gfw.global/3yWa8Q2>

10 See: <https://gfw.global/3idQfh>

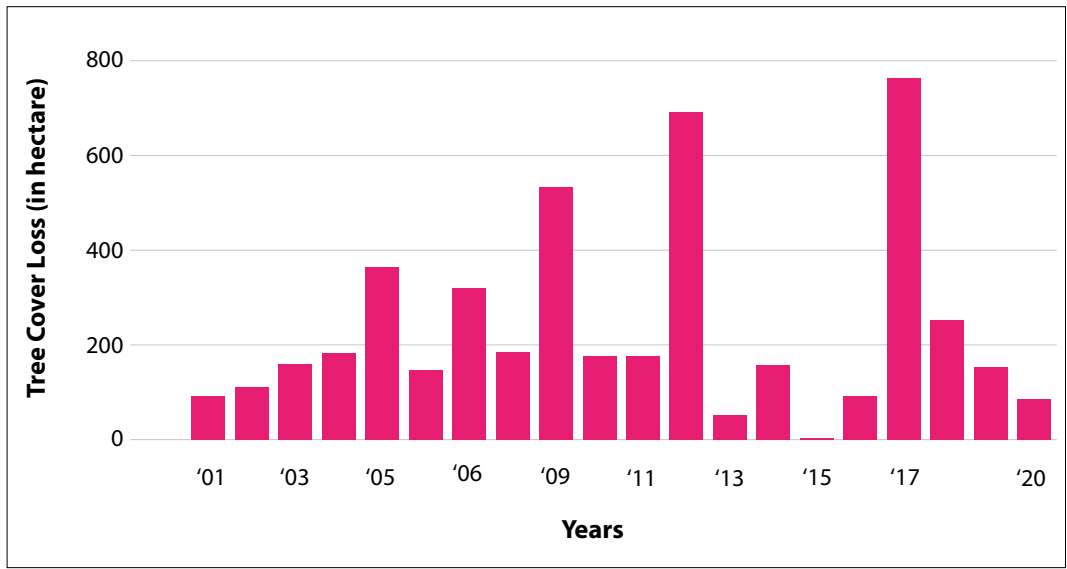


Figure 2a. Total tree cover loss in the study area from 2001 to 2020 (>30% tree canopy: these estimates of natural forest loss do not take tree cover gains from reforestation and afforestation into account).

Source: GFW (2021)¹¹

the atmosphere¹² (Figure 3). Over the same period, at the district level, GHGs emissions were highest in Jumla (660 kilotons (kt) of CO₂e, including 502 kt of CO₂ and 158 kt of other GHGs), followed by Kalikot (562 kt of CO₂e; 422 kt of CO₂ and 140 kt of other GHGs), Jajarkot (448 kt of CO₂e; 344 kt of CO₂ and 104 kt of other GHGs), Rukum East (336 kt of CO₂e; 247 kt of CO₂ and 89 kt of other GHGs), Rukum West (274 kt of CO₂e; 205 kt of CO₂ and 69 kt of other GHGs), Dolpa (245 kt of CO₂e; 184 kt of CO₂ and 61 kt of other GHGs) and Rolpa (214 kt of CO₂e; 168 kt of CO₂ and 46 kt of other GHGs).

Even though Nepal is among the smallest contributors to GHG emissions, it is ranked among the world’s 10 most vulnerable countries to the impacts of climate change because of its high poverty rate and low adaptive capacity (INDC 2016). Temperatures

in western Nepal have increased by an average of 1.2°C over the last 36 years (1975–2010). This is also reflected in the climate change vulnerability index:¹³ this ranking index refers to how vulnerable a system is to the negative impacts of climate change, such as climate variability and extremes, as well as how well it can deal with them (Houghton et al. 2001). The climate change vulnerability index for Dolpa, Kalikot and Jajarkot districts ranges from 0.601 to 1.00, which is very high in comparison to other districts in the study area and in the Karnali province, the largest province of Nepal (MoFSC 2016).

Due to unsustainable harvesting practices and infrastructural development, forest fires are one of the major causes of deforestation in Nepal (Chaudhary et al. 2001). In Nepal, forest fire events have increased over the years. Warm winters and prolonged droughts have triggered wildfires, burning thousands of hectares of forest and wildlife habitats inside and outside protected areas. There were

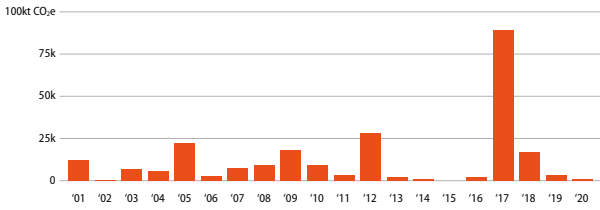
11 See: <https://gfw.global/3y2ICRN>

12 All-important ecosystem carbon pools (aboveground biomass, belowground biomass, dead wood, litter, soil) and greenhouse gases (CO₂, NH₄, N₂O) are included in the emissions computed for the study area and are assumed to take place in the year of disturbance.

13 Climate change vulnerability index assesses human vulnerability to extreme climate incidents and changes in weather patterns over the next 30 years.

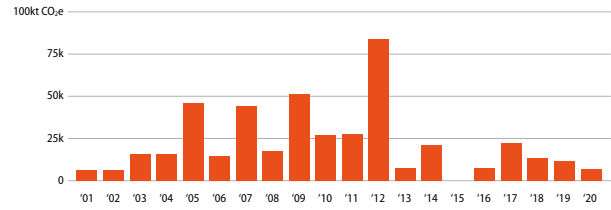
FOREST-RELATED GREENHOUSE GAS EMISSIONS IN DOLPA

Between 2001 and 2020, an average of 12.3kt per year was released into the atmosphere as a result of tree cover loss in Dolpa. In total, 245kt of CO₂e was emitted in this period.



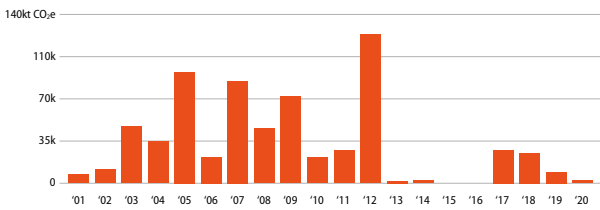
FOREST-RELATED GREENHOUSE GAS EMISSIONS IN JAJARKOT

Between 2001 and 2020, an average of 22.4kt per year was released into the atmosphere as a result of tree cover loss in Jajarkot. In total, 448kt of CO₂e was emitted in this period.



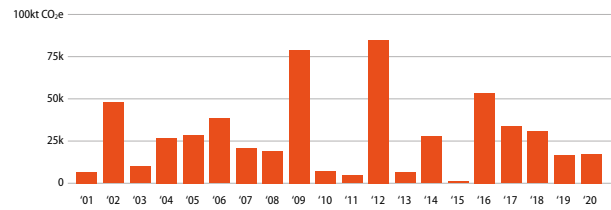
FOREST-RELATED GREENHOUSE GAS EMISSIONS IN JUMLA

Between 2001 and 2020, an average of 33.0kt per year was released into the atmosphere as a result of tree cover loss in Jumla. In total, 660kt of CO₂e was emitted in this period.



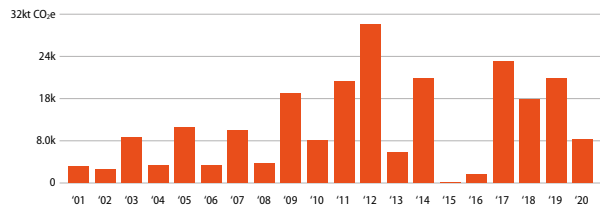
FOREST-RELATED GREENHOUSE GAS EMISSIONS IN KALIKOT

Between 2001 and 2020, an average of 28.1kt per year was released into the atmosphere as a result of tree cover loss in Kalikot. In total, 562kt of CO₂e was emitted in this period.



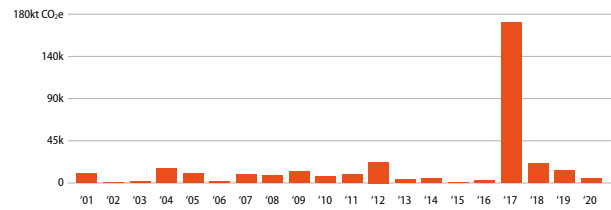
FOREST-RELATED GREENHOUSE GAS EMISSIONS IN ROLPA

Between 2001 and 2020, an average of 10.7kt per year was released into the atmosphere as a result of tree cover loss in Rolpa. In total, 214kt of CO₂e was emitted in this period.



FOREST-RELATED GREENHOUSE GAS EMISSIONS IN RUKUM EAST

Between 2001 and 2020, an average of 16.8kt per year was released into the atmosphere as a result of tree cover loss in Rukum East. In total, 336kt of CO₂e was emitted in this period.



FOREST-RELATED GREENHOUSE GAS EMISSIONS IN RUKUM WEST

Between 2001 and 2020, an average of 13.7kt per year was released into the atmosphere as a result of tree cover loss in Rukum West. In total, 274kt of CO₂e was emitted in this period.

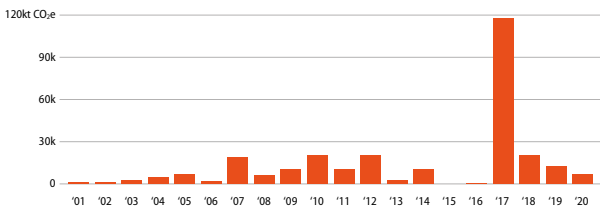


Figure 2b. Tree cover loss by district, from 2001 to 2020 (>30% tree canopy: these estimates of natural forest loss do not take tree cover gains from reforestation and afforestation into account)
Source: GFW (2021)⁴⁻¹⁰

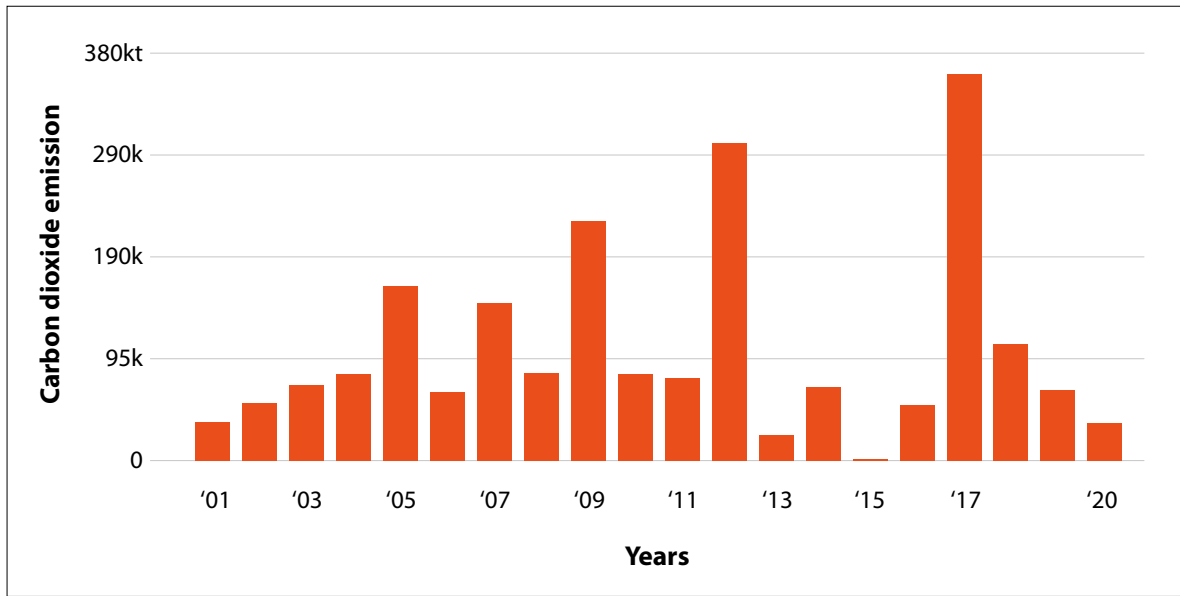


Figure 3. Total CO₂ emissions from biomass loss in the study area
 Source: GFW (2021)¹⁴

35,374 wildfires reported between 2000 and 2016 via MODIS¹⁵ satellite images, with a burnt area of 1,723,920 hectares (Bhujel et al. 2017). Wildfires are also frequent in the study area. Between 2003 and 2013, the number of annual active fire days in the study area varied from 1 to 24 days, with Jajarkot district experiencing the most fire days, ranging from 15 to 24 (Matin et al. 2017). Data on active fire days was collected from the Moderate Resolution Imaging Spectrometer (MODIS) on NASA’s Terra and Aqua satellites; this data identifies the location of the fire. The majority of the fire cases in the study area were reported in April, November, and December.

Selection of citizen scientists

The involvement of local communities is crucial for the success of a conservation

program. Since local people know their forests and wildlife best, involving them directly from the onset can build a sense of ownership and ensure active participation in the program (Williams et al. 2011). Community-based monitoring programs can raise local awareness on the long-term value of sustainably managed forests and on the aesthetic value of natural ecosystems. Through citizen science programs, local actors can strengthen their capacity to use structured, scientific techniques to assess habitat quality and conservation threats. Science-based monitoring techniques can empower local forest users by not only educating them about conservation and sustainable management of forests but also motivating them to engage in initiatives to protect endangered species. For instance, in western Nepal, a community-based monitoring program has helped to combat illegal poaching of endangered species, like the Himalayan red panda, by locating and dismantling traps and snares.

In the study area, two people were selected from each CFUG to act as citizen scientists based on their knowledge of the local

14 See: <https://www.globalforestwatch.org/>
 15 The Moderate Resolution Imaging Spectroradiometer (MODIS) plays a vital role in the development of validated global, interactive Earth system models that can assess land use changes globally and accurately enough to assist policymakers in devising measures to protect the environment. See: <https://modis.gsfc.nasa.gov/about/>

topography, flora and fauna and literacy to handle data sheets and equipment (e.g. smartphone, GPS, Vernier caliper¹⁶). CFUGs gave priority to livestock herders and ex-poachers meeting these criteria.

GFW platform

Global Forest Watch (GFW)¹⁷ is an open-source platform providing real-time spatial data collected through remote-sensing technologies, as well as tools and technology to better monitor and analyze forest changes across the world (Zhang et al. 2020). This platform, launched by the World Resources Institute (WRI) in 2014, is a free forum facilitating community involvement in forest cover monitoring (Hansen et al. 2016). It offers users the possibility to create customized datasets focusing on their own areas of interest. Globally, GFW allows the monitoring of over 50 million hectares of forest (Zhang et al. 2020), and more than 2 million people, including researchers, conservationists, law enforcement officials, and local and indigenous communities are now using this platform to assess forest cover changes (Ren et al. 2015; Allan et al. 2017; Curtis et al. 2018; Yang et al. 2019). This innovative technology has empowered local communities to better monitor their forests despite their limited resources.

GFW datasets typically include information on:

- forest changes: deforestation alerts, fire alerts and tree cover changes at different resolutions, frequencies, and scales;
- land cover: data on tree cover, tree height and tree plantations, including coverage and distribution of different forest types, such as intact forest landscapes, mangroves, or primary forests;
- land use: legally protected areas, areas collectively held by indigenous people and local communities, as well as areas allocated by the government for different commodities and infrastructure;

- carbon stocks: potential carbon sequestration rate, carbon emissions rate, and carbon density values in topsoil and aboveground living woody biomass in different forest types, including mangroves;
- biodiversity: localization of biodiversity hotspots and critical conservation sites harboring different endangered species, effects of forest changes on global biodiversity intactness¹⁸.

GFW builds upon coarse spatial and high temporal resolution datasets such as:

a) *Global Land Analysis & Discovery (GLAD)*

The Global Land Analysis and Discovery (GLAD) laboratory¹⁹ at the University of Maryland monitors land use changes around the world and assesses their causes and impacts. This dataset is the first Landsat-based alert system for tree cover loss produced by the University of Maryland, assisted by GFW. These GLAD alerts have a 30 m resolution, compared to 250 m for MODIS imagery. Therefore, they can track tree cover loss much more precisely. GLAD alerts particularly cover land areas between 30° north and 30° south (Hansen et al. 2016).

b) *Visible Infrared Imaging Radiometer Suite (VIIRS)*

The Visible Infrared Imaging Radiometer Suite (VIIRS),²⁰ aboard the NOAA/NASA Suomi National Polar-orbiting Partnership (SNPP) weather satellite, is the most recent fire tracking tool used by FIRMS²¹ to track fire incidents around the world in near real time. VIIRS sensors collect the information and analyze it with a fire detection algorithm to mark active fires. The VIIRS dataset has substituted the previous MODIS active fires dataset of GFW. Its higher spatial resolution of 375 m, instead of 1 km, and improved

18 i.e. on the extent to which a land site's original biodiversity is preserved in the face of human land use and related pressures (Newbold et al. 2016).

19 See: <https://glad.umd.edu/>

20 See: <https://www.globalforestwatch.org/blog/fires/fighting-fires-with-satellites-viirs-fire-data-now-available-on-global-forest-watch/>

21 The NASA Fire Information for Resource Management System. See: <https://firms.modaps.eosdis.nasa.gov/>

16 An instrument for making very accurate linear measurements

17 See: <https://www.globalforestwatch.org/>

night-time performance allows the detection of smaller fires (even at night) and a more accurate delimitation of fire perimeters²². Under good atmospheric conditions, such systems have fair coverage and provide near-real-time data to many monitoring applications. The main drawback of such sensors is their coarse spatial resolution, which is nonetheless sufficient for many land use applications.

Forest Watcher mobile application

In partnership with Google, the Jane Goodall Institute and the National Forestry Authority in Uganda, WRI has launched a free open-source software called Forest Watcher, available via both the Apple App Store and Google Play Store²³ (WRI 2019). Data can be stored in the mobile device when it is not connected to the internet. The Forest Watcher mobile application makes satellite-derived alert systems and different spatial datasets from GFW available offline, including in the field. Regardless of internet connectivity, the users can: delineate their areas of interest; obtain near-real-time deforestation (GLAD) and fire (VIIRS) alerts; navigate different locations to explore and create reports based on what they find on the ground.

In addition, the web version of Forest Watcher can be further customized. It offers users options to upload their own contextual data, edit reporting templates and share created reports with team members (Forest Watcher 2021).

In association with the relevant Division Forest Offices and local council bodies, we conducted a series of workshops on GFW's forest monitoring and alert system for frontline FGs and CFUGs. The workshops included both theoretical and practical sessions about the direct use of *Forest Watcher* in forest inventory processes. In total, we trained 68 FGs and CFUG members from 34 community forests (CFs) in seven districts of western Nepal. Following the workshops, the trained

forest watchers traversed a transect length of 204 km, monitoring 6,657 hectares of CF areas from March to December 2020.

Results

Over the monitoring period (March to December 2020), 2,983 GLAD alerts were reported for deforestation. The highest number of deforestation alerts (890) was reported for the month of November, when the climate in the study area is pleasant and suitable for deforestation activities, after a hot and rainy summer. At the district level, the highest number of GLAD alerts was reported in Jumla (1,809), followed by Dolpa (670), Jajarkot (170), Rukum East (238), Rukum West (82), Kalikot (243), and Rolpa (71).

Over the monitoring period, 285 VIIRS fire alerts were recorded within the study area (**Figure 4a**). At the district level (**Figure 4b**), 68 fire alerts were reported in Jajarkot, followed by Kalikot (65), Dolpa (62), Rukum West (39), Rukum East (30) and Jumla (21). No fire alerts were recorded in Rolpa.

Discussion

It is difficult to reduce emissions from deforestation and forest degradation based on performance due to a lack of precise and consistent forest data at the global scale. The Forest Watcher application has helped local communities patrol forests by making data collection and reporting more efficient and drastically reducing the risk of errors. These data have helped improve forest conservation efforts and develop long-term effective conservation plans.

As some citizen scientists have only an elementary school education and limited English proficiency, Forest Watcher could be improved by providing translations into Nepal's various native languages. As the application is still in development, the user interface could still be improved.

The tool dramatically reduces the time needed to obtain precise and reliable

22 See: <https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms>

23 Accessible here: <https://forestwatcher.globalforestwatch.org/>

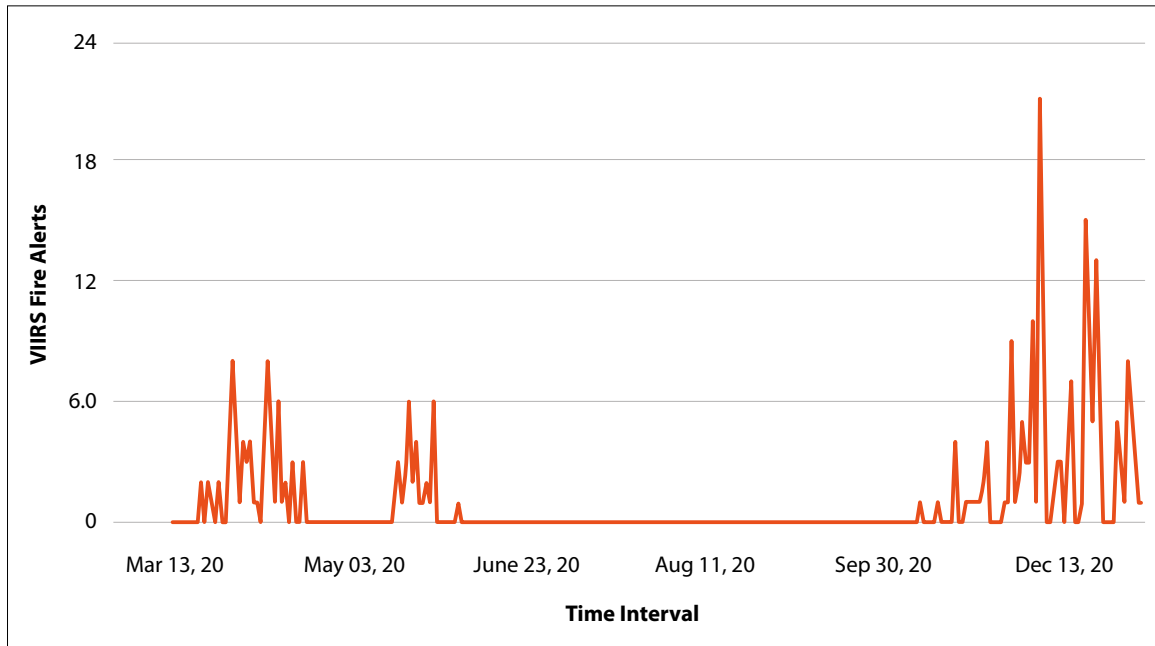


Figure 4a. Total VIIRS Fire Alerts in the study area

Source: GFW (2021)²⁴

forest data. Today, anyone with an internet connection can obtain detailed and easily comprehensible information, updated every 16 days, on where and at what speed forests are disappearing or regrowing worldwide at a spatial resolution of up to 30 meters. Governments can use this information to strengthen law enforcement, NGOs to advocate for better forest protection, and businesses to monitor deforestation in their operations and supply chains. Forest Watcher depends on citizen scientists to help validate and ground-truth the data. Users are encouraged to submit georeferenced comments, photos, and videos to compare on-the-ground alerts with the latest satellite images.

This application has been used to report illegal encroachment in Jajarkot and Jumla districts in western Nepal and is helping to better mobilize resources to contain forest fires in the Kalikot district. It has also been used by local forest guardians in Kalikot district to regularly monitor community forests. Traps and snares have been photographed and documented during regular patrolling. Data are then centralized on a server, with

georeferenced comments, photos and videos of the traps and snares taken by the forest guardians.

Although tree cover loss in the study area has varied by district over the last 20 years, the overall rate appears to be decreasing. Shrestha et al. (2018) found that the districts with the most community forests experience the smallest tree cover losses and the largest tree cover gains. A total of 223 CFUGs manage community forests in Rolpa, and 101 in Jumla (Kanel et al. 2006). This highlights the effectiveness of CFUGs at improving forest cover and overall forest conditions in Nepal.

As climate change impacts precipitation, changing rain and snow patterns and shifting plant communities, fires are occurring more often, burning more intensely, and spreading more widely than ever. Such climate change-induced disasters have a cascading effect on food supply and security, agricultural production, and water availability, which can result in the loss of human lives and livelihoods. The accurate and real-time monitoring of such events using digital technologies and citizen engagement can therefore make a critical contribution to sustainable development. Data received

²⁴ See: <https://www.globalforestwatch.org/>

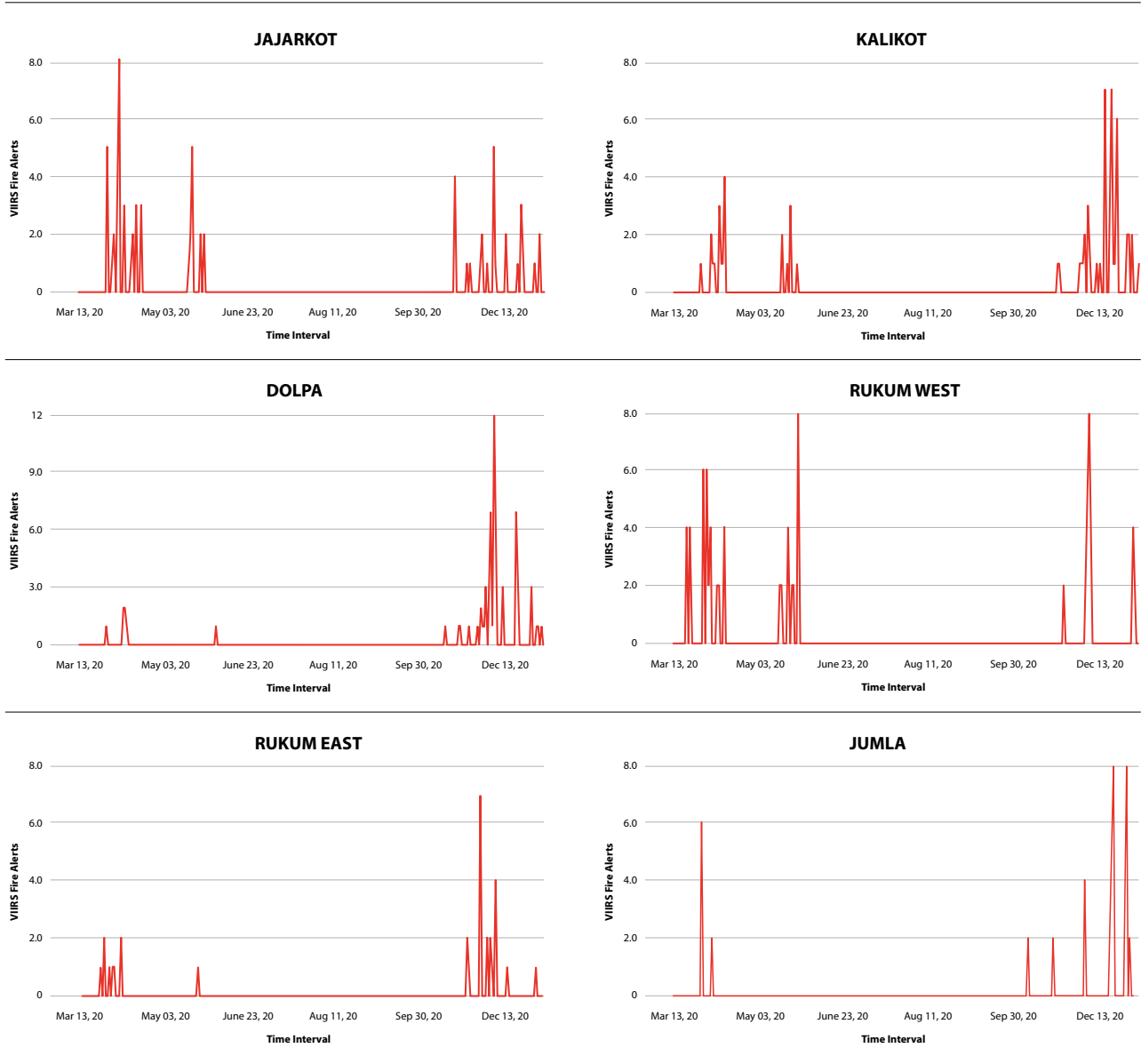


Figure 4b. District-wise VIIRS Fire Alerts
 Source: GFW (2021)²⁵

from forest watchers are being shared in real time with relevant CFUGs, local partner organizations and the Divisional Forest Offices, enabling them to react promptly to concerns and threats recorded during monitoring. The introduction of citizen science into forest management has proven very successful in Nepal.

Conclusion

A number of factors are contributing to deforestation and forest degradation in Nepal, including habitat degradation, illegal harvesting, wildfires, agricultural expansion, urbanization and infrastructure development, as well as weak state control over the land. Marginalized communities are the ultimate victims of deforestation, climate change and biodiversity degradation. Community forestry and citizen engagement in forest monitoring and management can play a

25 See: (<https://gfw.global/2RjDPjX>) (<https://gfw.global/3vNJdnr>) (<https://gfw.global/2RkjWCz>) (<https://gfw.global/3uOdBgm>) (<https://gfw.global/3uOdwcy>) (<https://gfw.global/3uPkZb4>)

critical role in primary forest conservation and in the sustainable management of forest ecosystems, thus contributing to climate change mitigation and adaptation, biodiversity conservation, food security, poverty alleviation and social inclusion.

In this context, the Forest Watcher mobile application and personal digital assistants (PDA) have significant potential to enhance community participation in the data collection process, thus contributing to the successful adoption of CBFM. The integration of remote sensing technologies like Forest Watcher into local forest monitoring efforts offers considerable computational capacity at just the tap of a finger, contributing to more accurate and rapid forest monitoring while saving time and resources. Forest Watcher has enabled forest stakeholders to visualize and evaluate forestry-related information in ways that benefit the decision-making process, and it will be crucial in enhancing present conservation efforts and devising long-term effective forest conservation plans.

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Google Earth Engine, an innovative technology for forest conservation

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Abstract

Millions of satellite images of the Earth's surface are produced each day. However, these images can be difficult to access and analyze as they are scattered across different websites, and processing them can take weeks or months due to the computing limits of office computers. Google Earth Engine (GEE) can help solve these problems. GEE is a web application where all open-access images of the Earth's surface are compiled. The application benefits from the computing power of thousands of computers at Google's data centers, thus reducing the time needed to conduct land cover analysis at national, regional and planetary scales. Since its creation in 2010, the application has been used in a wide range of fields such as agriculture, economics, medicine, and forestry. For instance, in 2013, Dr. Matthew C. Hansen (University of Maryland, the United States of America) has automated the analysis of Earth's forest cover using GEE, allowing analyses of forest cover loss to be constantly updated (Hansen et al. 2013).

During his eight-month master's thesis, the first author (TS) mapped oil palm plantations in Sumatra, Indonesia using GEE. The map had a high overall accuracy and compared well with the official Indonesian statistics. The code and the input data are freely available on TS's GitHub account for future experimenters to apply in different years or regions. Similarly, the co-authors (SBW, AR and JL) are currently using GEE to map cashew monocultures in Sindhudurg district (southern Maharashtra state, India). These studies, made possible by the use of GEE, were a first step toward the close monitoring of oil palm and cashew plantations, which are important drivers of deforestation in Indonesia and India.

Such land use monitoring could be programmed to be constantly self-updating like in Dr. Hansen's project. A small number of resource persons could be trained to use GEE and provide inputs for such programs.

These land use monitoring tools can help enforce forest protection laws and identify companies sourcing oil palm or cashew from protected areas. In addition, the information acquired using GEE can assist organizations managing oil palm sustainability certification schemes in excluding companies that drive deforestation or source material from protected areas. People equipped with GEE skills can play a key role in influencing landscape planning and making adequate policies in the forestry sector. These tools can help prevent or reduce CO₂ emissions due to commodity-driven deforestation, as well as protect the abundant biodiversity present in natural forests.

Keywords: *remote sensing, google earth engine, deforestation, land-use change, oil palm.*

Introduction and background

Background

Deforestation for agricultural expansion is a persistent global threat to natural ecosystems and contributes to carbon dioxide emissions and climate change. The expansion of agricultural land has been driven by increasing human population and growing demand for food, fuel and fiber. The challenges associated with monitoring the conversion of natural ecosystems to agricultural land can be informed using improved technologies for land cover and land use mapping.

Google Earth Engine (GEE) was developed by Google in 2010 to help land planners acquire and analyze satellite imagery at a planetary scale. Millions of satellite images of the Earth's surface are produced each day. However, they are often scattered across different sources in various data formats and can be challenging and time-consuming to analyze due to the computing limitation of personal computers.

GEE is a cloud-based platform powered by Google Cloud Platform and can be operated seamlessly with other online services provided by Google. With the help of GEE, ready-to-use datasets can be easily loaded and processed. Then, the processed data and analyzed results can be stored and exported for future use. GEE has its own application programming interface (API), which includes a library of operators in both JavaScript and Python computer languages,

making it accessible to a wider community. The platform increases accessibility to high-performance computing resources for processing large geospatial datasets (Gorelick et al. 2017). GEE provides users with access to the computational power of thousands of computers from Google's data centers through its online code platforms.

The GEE code platform¹ works with JavaScript, while Python users can deploy the computational power through Google Colab,² an online Python application for general purposes that also allows the use of GEE, as well as free access to the computing power of Google.

It is worth mentioning that among its vast number of libraries, GEE incorporates most of the state-of-the-art machine learning (ML) methods, which can be easily called and applied to the loaded or processed geospatial datasets as the algorithms have been packed into three packages (namely Classifier, Clusters and Reducer). For example, the widely-used classification methods for land use classification, like random forest classifier and other tree-based classifiers, are all included in the Classifier package and can be called with a few lines of code.

When dealing with more complex models or larger training datasets, GEE also works well with TensorFlow, which is an open access library to facilitate efficient ML analysis. The

1 Accessible at <https://code.earthengine.google.com/>

2 See: <https://research.google.com/colaboratory/faq.html>

built-in functions and packages make the learning curve of GEE much less steep. Moreover, the active online community of GEE can be greatly helpful to learners. Not only do users make use of previous code and packages, but GEE has also recently created a feature to integrate any code into a shareable user interface called Earth Engine Apps. Such apps can use open access code developed by users and leverage GEE's data catalog and analytical power to detect deforestation and land use change.

Since its launch, GEE has been used worldwide in various fields spanning agriculture, ecology, economics, forestry and medicine (Kumar and Mutanga 2018). GEE is a very promising innovation that, by providing large datasets and high computation power to users, can facilitate the mapping of Earth's land cover at national, regional and planetary scales (Hansen et al. 2013).

Objective of the article

This article aims to introduce readers to GEE with two examples of its uses for land cover mapping: (i) industrial oil palm detection in Indonesia; and (ii) differentiating cashew from forest cover in India. These two case studies provide insights about the implementation, impact and constraints of this innovative technology for monitoring agricultural land cover that commonly encroaches into forests.

Description of the innovation

Industrial oil palm detection in Indonesia

The first author (TS) mapped oil palm plantations for the year 2015 in Riau, Jambi, and South Sumatra, three provinces of Indonesia known for their large areas dedicated to oil palm (Sarzynski et al. 2020).

Imagery from two optical satellites, Landsat 7 and Landsat 8, and one radar satellite, Palsar, were all sourced and pre-processed on GEE. The analysis included running the classification of land cover separately for each type of satellite imagery and when optical and radar imagery were combined

(Joshi et al. 2016). Apart from the wavelength bands used in the satellite images, a range of indices (e.g. NDVI – normalized difference vegetation index,³ EVI – enhanced vegetation index,⁴ etc.) were calculated and included in the classification process, which involved a random forest (RF) algorithm,⁵ a common ML method based on building a large number of decision trees to classify six land cover types: forest, forest-shrub mosaic, oil palm, bare-ground crop, built-up area, and water. Both the analysis and accuracy assessment were conducted using the GEE API.

The overall accuracy of the resulting map, which is the number of correctly classified pixels over the total number of pixels, reached 84 percent. The pixels used to calculate this overall accuracy were selected for each land cover type from polygons we delineated in Google Earth Pro. Our map estimation of oil palm area in the three provinces (4.4 million ha) compared well with the official Indonesian statistics (4 million ha). We compared our technique with those in two other studies to map oil palm in the same area. Our technique provided a closer estimate of oil palm extent to the official statistics than the other studies, but with a substantial number of discrepancies with the two maps of the other studies. Our map of oil palm was compared to a map of protected areas to detect potential illegal deforestation and encroachment. This comparison showed that oil palm plantations encroached on 3 percent of the protected areas in these provinces in 2015.

This work can contribute to closely monitoring oil palm plantations and better identifying whether and where oil palm plantations have expanded over forests and caused deforestation. The code and source data are freely available on GitHub online repository⁶ for other researchers to apply in different years or regions. Subsequent maps drawn from different years can highlight changes in

3 See: https://en.wikipedia.org/wiki/Normalized_difference_vegetation_index

4 See: https://en.wikipedia.org/wiki/Enhanced_vegetation_index

5 See: https://en.wikipedia.org/wiki/Random_forest

6 See: https://github.com/thuansarzynski/GEE_CombinedLandsatSAR_oilpalm

land use and land cover over time and inform policymakers and law enforcement officials on where natural resources are threatened. For example, a sustainable certification program could exclude oil palm companies establishing plantations on forested land.

Differentiating cashew monocultures from forests in India

While many studies have already mapped crops such as oil palm and coffee, cashew monoculture has not yet received much research attention. Cashew is currently grown across 33 tropical countries that also host high levels of biodiversity (FAOSTAT).⁷ The co-authors (SBW, AR and JL) are currently using GEE to map cashew monocultures in Sindhudurg district (southern Maharashtra, India). India is the second-largest cashew producer in the world, and Sindhudurg is one of the country's top cashew-producing districts (C-DAP Sindhudurg 2012; FAOSTAT⁷). The forests in Sindhudurg fall in the Western Ghats global biodiversity hotspot⁸. Most of them are privately-owned forests and serve as a wildlife corridor (Myers et al. 2000; Punjabi and Kulkarni 2015). In recent years, cashew monocultures have increasingly replaced forests in this landscape.

The authors obtained and pre-processed optical (LANDSAT-8) and radar (SENTINEL-1) imagery from February to May 2020 using GEE. Pre-processing involved speckle filtering and mosaicking the image to remove cloud cover. For analysis, random forest (RF) and classification and regression tree (CART)⁹ algorithms were run on combined optical and radar imagery using polygons of the following land cover categories: forest, monoculture cashew, barren land, crop land, and water

bodies (delineated in Google Earth Pro¹⁰ using on-ground field observations).

The total extent of land under cashew cultivation in Sindhudurg according to our preliminary GEE analysis was 118,000 ha using the RF algorithm, and 74,500 ha using the CART algorithm. In 2018, Maharashtra had 191,450 ha of land under cashew cultivation, of which Sindhudurg is known to contribute approximately 41.1 percent or 78,685.9 ha (Sengar et al. 2012; Directorate of Cashew nut and Cocoa Development 2018).

The 58 percent difference between RF and CART algorithms is due to differences in how they work, with the CART algorithm being more robust for outlier predictors. In the absence of official government records for 2020 for Sindhudurg district, our preliminary results using the CART algorithm compare reasonably well with 2018 government statistics on cashew extent. However, this is an ongoing study, and future analyses should also evaluate the performance of other classifiers such as the support vector machines (SVM)¹¹ algorithm and use accuracy assessments to compare algorithms.

This project will enable an evaluation of the most suitable methods that can be used to map cashew plantations in the Western Ghats, which could form the basis for future remote sensing studies that use GEE to map and detect cashew land use expansion. Mapping cashew monocultures using GEE can be a useful tool for conservation and land use planning. In the future, GEE could be used to monitor deforestation and cashew expansion and serve as a useful mapping tool for potential cashew sustainability certification programs.

7 See: <http://www.fao.org/faostat/en/#data/QC> (accessed 10 February, 2021).

8 According to Conservation International, an American non-profit environmental organization, to be qualified as a biodiversity hotspot, a region must have (a) at least 1,500 vascular plants as endemics, and (b) 30

9 RF is a non-parametric algorithm that uses a combination of decision trees to select the most suitable class for the pixel in question, while CART is a supervised algorithm that creates a binary decision tree and is more robust to outliers in predictors (Shaharum et al. 2020).

10 This software is now freely accessible. See: <https://www.google.com/earth/versions/>

11 SVM Constructs a 'hyperplane' or set of hyperplanes (hyperplane: a sub-space whose dimensions are one less than that of its model environment) in an infinite-dimensional space, which can further be used for image classification. See: <https://scikit-learn.org/stable/modules/svm.html> (accessed 24 March, 2021).

Results (implementation, impacts, constraints, enabling environment)

GEE implementation and dissemination

The GEE web application was originally created by Google engineers and mostly used by academics based in the USA for forest and vegetation land use and land cover studies (Kumar and Mutanga 2018). GEE was first developed to facilitate access to and analysis of large amounts of remote sensing data. However, the first users had to learn the programming language of the software and develop their own code and program to run land cover analyses. Academics were the principal users and developers of GEE since they had the required knowledge to create and implement a GEE program in their research. For example, the two-mapping projects described above were carried out by graduate students. The large effort of academics in developing GEE for land cover mapping and forest monitoring generated a new scientific literature about GEE implementation and thereby facilitated capacity building for individuals, who disseminated the technology to the private sector. Unfortunately, GEE has yet to be widely adopted by non-profit organizations (NGOs) or government agencies due to the knowledge gap in programming skills and geographical information system (GIS) software.

Potential contribution of GEE to sustainable forest management

GEE can have an impact by making satellite imagery accessible to a wide range of users and providing access to powerful computational tools for remote sensing through its web application. The use of remote sensing to generate information on land cover change, in particular on agricultural expansion into tropical forests, enhances our understanding of these processes. GEE can help monitor land cover changes and identify the main drivers of deforestation. However, on-the-ground interviews and field data collection is necessary to ground-truth the map resulting from remote sensing analysis using GEE and to gain a deeper

understanding of causal relationships and responsible actors driving the process of deforestation. A combination of field-based data collection and tracking land cover change through satellite imagery could be used to inform future policies addressing land use changes and deforestation.

GEE can also enhance forest governance and enable forest owners or civil society organizations to detect changes in forest land cover and report these changes to government agencies. Civil society organizations involved in forest protection and climate change policies (e.g. FLEGT – Forest Law Enforcement, Governance and Trade, REDD – Reducing Emissions from Deforestation and Forest Degradation, NDC – Nationally Determined Contributions of the Paris Agreement) could hold governments and companies accountable for trends in deforestation in countries and corporate sectors respectively.

Constraints to dissemination and adoption

The main constraint to implementation is the limited number of people proficient in using GIS software. GEE itself is not complicated to implement once the code is accessible; however, users need basic knowledge of GIS to use the software. While using a GIS software, users can format the retrieved maps from GEE and integrate them into reports for policy advocacy. Countries and organizations who want to use maps and geographic information in policymaking and advocacy require people with such expertise. Launched in 2010, GEE is a comparatively young platform and is yet to gain widespread use and popularity. Future efforts can be focused on reaching out across all sections of academia and policymakers alike so that the multi-faceted benefits of GEE can be realized in practice. A more costly solution is to develop a third-party software based on GEE to guide users in implementing a specific code. A handful of software based on GEE for land monitoring already exist: for example, Collect Earth, which provides users with high-resolution satellite imagery to support the monitoring of agricultural lands, quantifying deforestation and land use changes (Saah et al. 2019).

Enabling factors to facilitate implementation

A handful of companies and organizations have already developed remote sensing tools to monitor forest evolution. GEE and other tools like Terra-I and Global Forest Watch¹² are already being used to monitor forest cover. In 22 African countries that have subscribed to warnings from services based on satellite imagery to detect decreases in forest cover, the probability of deforestation decreased by 18 percent in two years compared to the period from 2011 to 2016. Thanks to such warning systems, government agencies were better able to enforce existing forest protection laws or contribute to policies that reduced deforestation (Mofette et al. 2021).

Conclusions and wider implications of findings

People able to use GEE or equivalent remote sensing technologies can play a key role in influencing land use planning. For example, in Indonesia and India, such expertise has been used to map deforestation ‘hotspots’ and to identify the main drivers of this deforestation. Supported by the international community, civil society organizations can hire staff with GIS skills to analyze land use imagery to identify illegal deforestation and hold the guilty parties accountable.

GEE and remote sensing mapping tools can help future sustainability programs monitor oil palm and cashew land use expansion to better understand prior land use for commodity expansion, a key requirement when assessing corporate compliance with sustainability standards. It can hence be an effective landscape management tool for conservationists, regulators, and policymakers.

International donors should promote projects using such remote sensing tools for forest protection and advocacy for better environmental policies. Policy instruments like FLEGT, REDD+, and the Paris Agreement

should seize the potential of GEE and remote sensing technologies to hold governments accountable for forest protection. For example, the Measurement, Reporting and Verification (MRV) provisions in the Paris Agreement should require land cover maps for mitigation based on land use.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO or CIFOR/FTA.

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12 See: <https://www.globalforestwatch.org/>

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Follow the water: Advanced technologies for demonstrating forest–water–community relationships

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Abstract

Forests play an important role in water circulation across the Earth, affecting both rural and urban communities alike. Conversely, by following the cycle and path of water through forests and communities, local residents can better assess risks from deforestation, find a basis for legal actions to prevent further destruction, plan reforestation efforts efficiently, and even design future urban communities strategically.

There are existing tools created specifically for mapping forest data, predicting floods and droughts, or managing forest data. However, there is currently no application that unifies these tools into a platform that pro-actively engages the mainstream public; nor is there a way to assess impacts of forest changes on the water cycle. Environmental information must be delivered to a broad audience as it develops and must not be limited to those who actively seek information, as this is a very limited demographic. To disseminate information more efficiently, a solution could be integrated into existing ubiquitous mobile applications that many people use on a daily basis, such as social media.

Combining innovative technologies for data collection, analysis, modelling and dissemination can provide new perspectives on how to raise awareness on the multiple impacts of deforestation on the environment and ultimately on human livelihoods and well-being. In this paper, we introduce the concept of Snitch – an end-user application that integrates five primary technologies:

1. real-time satellite data and forest monitoring applications to map out changes in forest areas;
2. machine learning for flood and drought forecasts based on changes documented in satellite data;

3. plant/tree identification applications that track plant species with geolocation, integrated with a database of native species to assist in preserving biodiversity in reforestation efforts, and in identifying ideal species for problem areas;
4. blockchain technology for recording, verifying, and dispersing forest data as well as data transparency; and,
5. web/mobile-based social network applications to effectively disseminate data to a mass audience.

With mobile applications, data is made available and accessible to the worldwide public. This opens new avenues for both local and international attention – and possibly intervention – to be enhanced in a more timely manner.

Introduction and background

Direct effects of deforestation on humans include flooding, water supply disruptions (or even loss of water supply to urban areas), landslides, extreme and erratic climate fluctuations, and wildlife intrusions into urban areas when their natural habitats decrease or are completely lost. Deforestation can also cause decreases in rainfall, which threatens human food production in the long term.¹ Deforestation and forest degradation can disrupt ecological balances, allowing certain species of plants and animals to become dominant due to the loss of predator species that serve to keep those populations in balance. While some may be considered mere nuisances, invasive species can potentially affect food supply along with other aspects of human life. Deforestation can also generate increased health risks, such as a rise in human diseases, including zoonoses² due to closer interactions between animals and humans attributed to habitat loss and the expansion of human habitation into former wildlife habitats.

Combining innovative technologies for data collection, analysis, modelling and dissemination can provide new perspectives on how to raise awareness on the multiple impacts of deforestation on the environment

and ultimately on human livelihoods and well-being. This paper describes the idea of a Snitch platform, which could be developed as an end-user mobile application that would empower local communities to assess the potential effects of deforestation, quarries, mining, and clearing activities on the flow of water. For every area deforested, machine learning systems can generate simulations on where the water will flow based on the forest area left.

Description of the innovation

Snitch would combine various technologies in order to provide users with real-time information about environmental developments that could potentially affect them. This can be done using machine learning to simulate how water will flow based on the changes in the landscape as well as predicted rainfall for the year. Snitch would also empower people and communities, encouraging them to take control of their environment by allowing them to participate directly in its management through reporting systems, collaboration and cooperation with other users.

The functions that Snitch would offer

1. Consolidation of tools

Many advanced technologies, such as satellites, drones or sensor networks, can be used for forest monitoring and management.

1 See: <https://www.borgenmagazine.com/deforestation-new-threat-global-food-security/>

2 See: https://e360.yale.edu/features/how_forest_loss_is_leading_to_a_rise_in_human_disease_malaria_zika_climate_change

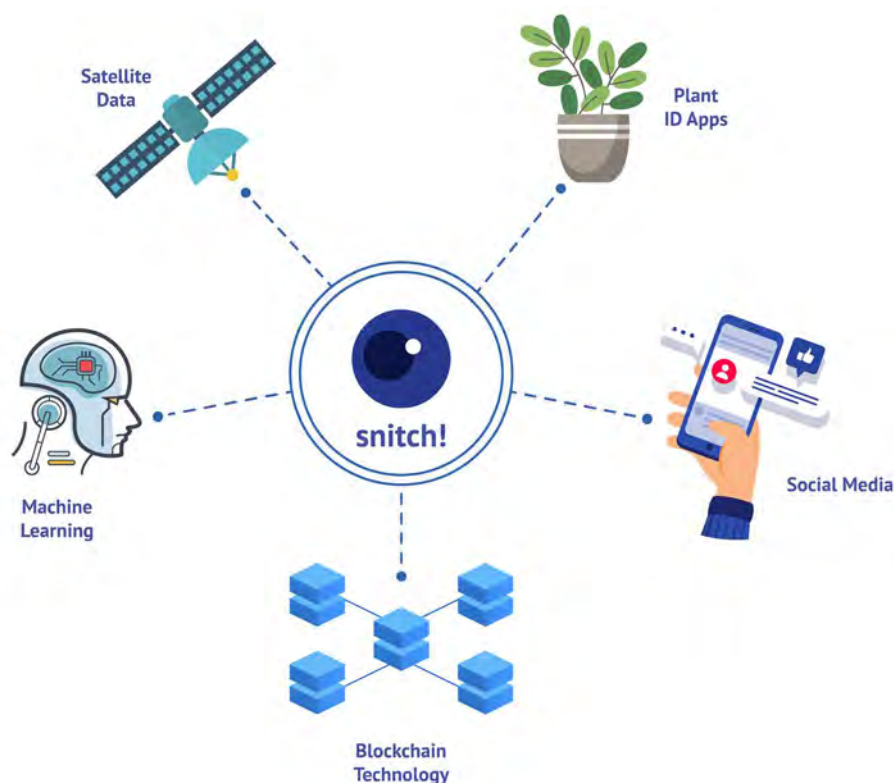


Figure 1. Five technologies that could be combined in the Snitch platform.

Source: Author

Forest Watcher, a web and mobile app created by the Global Forest Watch, uses different technologies to assist the Jane Goodall Institute's conservation efforts in Uganda since 2014. Different sensor technologies, such as synthetic aperture radar (SAR) and Light Detection and Ranging (LiDAR) have also been used together, with next generation improvements expected to resolve current limitations to their capabilities.

What is needed is a platform that consolidates and combines data from these tools into a single, easily understandable user interface.

2. Real-time monitoring

The objective of Snitch is to make forest data available to the general public in as close to real time as possible, and to make information readily available to regular users, such as through daily social media notifications.

3. Simulations of water flow

Through machine learning, simulations of how water flow will change based on changes in

forest data can be visualized and provided to users, along with warnings on potential dangers of flooding, drought, landslides, etc.

4. Social engagement and collaboration

Simply allowing simulations to be shared via social media can significantly raise the reach of information to a global scale. Snitch can also be integrated into other commonly used mobile applications with broad global reach such as Google Maps and social media.

The technologies that Snitch would combine

As illustrated in **Figure 1**, Snitch would combine five kinds of innovative technologies to streamline data dissemination and collaboration to support sustainable forest management.

1. Real-time satellite data and forest monitoring applications

The Food and Agriculture Organization (FAO) already supports National Forest Monitoring Systems (NFMS)³ for several countries. Tools such as Google Earth⁴ and Collect Earth Online⁵ can be used and integrated with other advanced technologies to help people monitor changes in forest areas in real time.

2. Machine learning

Using satellite data and weather forecasts, machine learning can be used to generate simulations of water flows, along with their potential impacts, such as floods and landslides, depending on the expected rainfall level. It can also generate predictions on possible water supply disruptions in cities based on deforestation around dams and water sources.

3. Plant/tree identification applications

Plant identification mobile apps can be used to aggregate a list of species found in forest areas through user submissions and Global Positioning System (GPS) data. They are also useful in identifying whether a prominent species is native to an area or not, or whether it is invasive and potentially detrimental to local ecosystems. Users can also contribute to a database of native tree species and their best use in order to conserving biodiversity.

4. Blockchain technology

Blockchain technology has a lot to offer in terms of recording, verifying, and instantly dispersing forest data on a massive scale. It offers the possibility of building identity and reputation systems to incentivize users to contribute accurate data. Reports from users can be time-stamped and archived in a record system that cannot be tampered.

3 See: <http://www.fao.org/redd/areas-of-work/national-forest-monitoring-system/en/>

4 See: <https://www.google.com/earth/>

5 See: <http://www.openforis.org/newwebsite/tools/collect-earth-online.html>

Financial incentives for deforestation are high, and mining corporations, illegal loggers and poachers and other actors are usually well-funded and possibly armed. Attacks on environmentalists have been on the rise in recent years.⁶⁶ Online profiles can be pseudonymous, which can help conceal the identities of foresters and environmental protectors. Anonymous users can easily take photos of environmental violations and violators and simply upload reports along with geodata and details to the network without fear of corporate or state-sponsored censorship. A dedicated archive web page can be made for this purpose.

Additionally, blockchain networks enable peer-to-peer transfers. Environmental advocates, depending on their reputation on the platform, can be funded individually, launch crowdfunding efforts for their initiatives, and receive donations directly from donors anywhere in the world.

5. Web/mobile-based social network applications

Some plant identification mobile apps, like PictureThis and PlantSnap, already include a social component that usually only works within the app itself. By integrating such apps into ubiquitous social media, the need to market and educate users into an entirely new tool can be significantly cut down and usage can be significantly increased.

Alarms on forest destruction can easily be disseminated on a large scale through social media notifications. The hope is that real-time information on undesirable changes to forest areas will push citizens to come together and take action as soon as possible. Through social network integration, users will also be able to discuss and collaborate on reforestation programs. Local communities will be enabled to work together to identify the best choices of tree and plant species for reforestation in a specific area, such as focusing on native and endemic species that would benefit native insect and bird populations.

6 See: <https://www.globalwitness.org/en/campaigns/environmental-activists/defending-tomorrow/>

Discussion

Snitch still requires software development and testing before implementation.

The Snitch platform could help prevent deforestation and forest degradation and support reforestation, improving livelihoods and enhancing health and safety. Snitch could help attract funding for local communities and contribute to boosting local micro-economies through ecotourism. The integration of even more advanced technologies such as virtual reality could be used to expand the tool to cover educational tours.

One limit of the platform is that it will only disseminate information to citizens. Ultimately, any action and political change to support ecosystem health will depend on local action and government support. The Snitch platform could even be used by local government units to support reforestation efforts or urban planning, including green infrastructures such as trees and parks.

Such tools also require public adhesion and education as well as an internet connection, which can be a challenge for poor communities in remote areas. This is expected to improve as satellite internet becomes more widely accessible worldwide.

Funding is another constraint facing this solution and most (if not all) other environmental protection solutions. Such social impact projects usually rely on donations. A monetization and incentive model is still to be crafted in order to make the project at least self-sustaining. If such efforts can be made profitable, there will be greater incentives for investors to fund them.

Conclusions and wider implications

Combining innovative technologies for data collection, analysis, modelling and dissemination can provide new perspectives on how to raise awareness on the multiple impacts of deforestation on the environment and ultimately on human livelihoods and well-being. Making forests a matter of global public discussion can open up several possibilities, such as bolstering international

collaboration on reforestation, forest protection, and even opening-up economies that thrive on sustainable forest-based products. Environmental health can be scored and gamified with financial incentives to help encourage and support local initiatives. A tool like the Snitch platform, described in this paper, can streamline the flow of information and enable users to collaborate on solutions. By following the movement of water through landscapes, technology can be used to provide users with a better understanding of how changes in forest landscapes impact them directly. The hope is to raise new generations of humans that understand how the planet works and consistently make planet-conscious decisions and strategies—whether in planning future cities, designing products, purchasing products for themselves, or conducting any other activity in all aspects of modern life.

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Spatial Monitoring and Reporting Tool (SMART) for innovative forest governance: Insights from Asia-Pacific countries

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Abstract

The Asia-Pacific region is one of the most biodiversity-rich regions in the world. However, poor law enforcement and governance in the region are a major threat to biodiversity conservation. Forest law enforcement is pivotal for forest and wildlife conservation, forest management and good governance. The Spatial Monitoring and Reporting Tool (SMART), developed through the combined efforts of nine global conservation agencies, is an innovative digital technology aiming at supporting and facilitating patrolling and law enforcement in forests and other biodiversity hotspots. It is an open-source tool that collects, stores, communicates and analyzes data collected by forest law enforcers on illegal activities, wildlife, patrol routes, and management actions. It helps to better understand and monitor the forest situation. It can also be used to evaluate the performance of forest rangers. Finally, it contributes to the adaptive management of natural resources by governments, community groups, and the private sector. Overall, it makes forest protection efficient and effective.

As of 2018, SMART is used in 765 protected areas in more than 60 countries, including 400 protected areas located in 18 countries in the Asia-Pacific region. Evidence from Bangladesh, Bhutan, Indonesia, Lao PDR, Nepal, Philippines, Thailand, and Vietnam shows that SMART has helped improve forest law enforcement and governance (FLEG) through efficient and effective patrolling and monitoring. SMART has increased employment opportunities in the forest sector and enhanced the transparency and accountability of forest governance. It has also provided a system for data storage and reporting.

However, a lack of human and financial resources and training often constrains the upscale of SMART implementation. To achieve SMART's full potential, governments and conservation institutions need to share the same vision on SMART. Governments, non-governmental

organizations (NGOs), financial institutions, and the private sector can help by providing financial and technical support to SMART users. Sharing success stories and lessons learned is also recommended to encourage more protected areas to adopt SMART.

Keywords: SMART, law enforcement, forest monitoring, patrolling, technology

Introduction and background

The Asia-Pacific region is one of the most biodiverse regions in the world. It houses 17 of the 36 global biodiversity hotspots¹ and seven of the 17 megadiverse countries² (IPBES 2018). Despite an increase in regional forest cover from 2010 to 2020, the number of wild mammals and birds has declined across the region (IPBES 2018; FAO 2020). A quarter of the region's endemic species are already threatened by poaching, the illegal wildlife trade, and forest clearing, leading to species decline (IPBES 2018). Damages caused by wildlife and forest crimes in the Asia-Pacific region are estimated to reach USD 19.5 billion annually (UNODC 2021). These illegal activities are partly a result of poor forest law enforcement coupled with corruption and lax regulations (UNODC 2021).

Forest law enforcement and governance (FLEG) is pivotal to forest management and conservation (Pescott et al. 2010). The Bali Declaration in 2001³ set the momentum for strengthening FLEG in the Asia-Pacific region. Moreover, increased awareness of the beneficial effects of efficient FLEG has drawn countries to commit through multilateral international agreements to checking illegal logging and sustainable forest management. Various international conventions and frameworks, such as the Convention on International Trade in Endangered Species (CITES), the Convention on Biological Diversity (CBD), the International Tropical

Timber Agreement,⁴ and the Asia-Pacific Economic Cooperation Environmental Vision Statement,⁵ also prescribe enhancing FLEG in the Asia-Pacific (Pescott et al. 2010).

An assessment of forest governance in the Greater Mekong Subregion⁶ showed that policies, legislations, and institutional frameworks are already in place; however, there are still challenges regarding implementation, enforcement, and compliance (Gritten et al. 2019). Participating countries at the Asia-Pacific Regional Workshop on FLEG, held in Kuala Lumpur, Malaysia (30 November – 1 December 2009), identified the use of information and communication technology as an emerging opportunity to strengthen FLEG (Pescott et al. 2010). Participants saw the wide availability of open and easy-to-use software for mapping and data gathering, the spread of social media, and affordable mobile data as opportunities to develop reliable tools for forest monitoring and governance (Castrén and Pillai 2015). With smartphones becoming a ubiquitous part of our everyday life, mobile-based applications seem to be a pragmatic way to enhance the efficacy of forest law enforcement in the tropics.

The Spatial Monitoring and Reporting Tool (SMART) makes forest law enforcement and monitoring possible using smartphones. Ranger patrols are the most common form of forest law enforcement globally (Wilfred et al. 2019). Patrol data are the basis for evaluating patrol effectiveness and park management strategies. They are also a source of evidence

1 See: <https://www.conservation.org/priorities/biodiversity-hotspots>

2 See: <https://www.worldatlas.com/articles/ecologically-megadiverse-countries-of-the-world.html>

3 See: <https://enb.iisd.org/events/forest-law-enforcement-and-governance-fleg-east-asia-ministerial-conference/summary-report>

4 See: https://www.itto.int/council_committees/itta/

5 See: https://www.apec.org/Meeting-Papers/Sectoral-Ministerial-Meetings/Environment/1994_environment/APEC%20Environmental%20Vision%20Statement

6 Including: Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam

of illegal activities. These are often collected through pen and paper and reported orally to park managers, meaning they can be easily lost or damaged (Mulqueeny and Cordon 2014, SNRD Asia/Pacific 2016). Patrol routes are planned using maps and photos (Mulqueeny and Cordon 2014). With SMART, effective and efficient patrol routes are planned through artificial intelligence. SMART also provides a systematic way of recording and reporting data, which contributes to the enhancement of FLEG.

This article discusses the experiences of selected countries in the Asia-Pacific region where SMART is widely implemented. It employs key informant interviews and a literature review to discuss the apparent positive changes in forest governance and monitoring brought by SMART.

Description of the innovation

SMART was developed in 2011 by nine international conservation organizations⁷ collaborating in a collective called the SMART Partnership⁸. The Partnership uses the 'SMART Approach' to promote the broad adoption and dissemination of SMART. The SMART Approach consists of developing the software and standards to ensure the effective implementation of SMART, as well as capacity-building and support to local users (Long 2016). The Partnership develops training materials and conducts free training for interested agencies and local users.

SMART is a set of free tools aiming at improving the management of protected areas (PAs). It allows the collection, storage, communication, and evaluation of data such as patrol efforts, patrol results, threats, and ecological surveys (SMART Partnership 2018). SMART enables PA managers to collect data on threats, patrol activities (i.e. areas

patrolled and patrol time), and ecological sightings. This information supports decision-making by PA managers and governments, including assessing the need for more staff or resources on the ground. Thus, SMART optimizes the investments made for conservation through the efficient allocation of staff, resources, and funds.

SMART consists of three platforms (SMART Partnership 2017, 2018):

- i. *SMART Mobile*, which uses the *CyberTracker* software,⁹ allows patrolling and data collection using smartphones or tablets. It does not require an Internet connection in the field, but the device needs to have a good battery life, work in rugged conditions, and record GPS points;
- ii. *SMART Desktop* is where data from SMART Mobile are transferred and stored in a database; and,
- iii. *SMART Connect* allows real-time reporting, data storage in a cloud database, and centralized management. It requires at least 1 Mbps Internet connection, a cloud-based server, and an information technology specialist.

SMART also contains several modules designed to support adaptive PA management. These modules allow efficient and effective forest patrolling, rapid ecological surveys, key species monitoring, data consolidation in a centralized database and data analysis, map generation for planning and reporting, real-time warning systems, real-time management and response to alerts, integration with other management tools and software, the creation of standardized reports, and the central management of PA networks (SMART Partnership 2018).

The SMART software can be downloaded for free on the SMART website.¹⁰ There are also

7 Frankfurt Zoological Society, Global Wildlife Conservation, North Carolina Zoological Park, Panthera, Peace Parks Foundation, Wildlife Conservation Society, Wildlife Protection Solutions, World Wildlife Fund, and Zoological Society of London.

8 See: <https://smartconservationtools.org/smart-partnership/>

9 See: <https://www.cybertracker.org/software/>

10 See: <https://smartconservationtools.org>

published materials on the website to guide SMART users.

The use of SMART is not reserved to experts or educated personnel. It can be configured and adapted to the local context and to the users' needs. It is available in various languages and includes icons easily understandable to uneducated users. SMART can be used in different ecosystems, whether terrestrial, marine, or freshwater, and can work on many platforms, such as Windows, Apple, or Linux. With the upcoming version 7, SMART will be accessible not only on Android but also on iOS smartphones (T. Lynam personal communication 11 February 2021).

The SMART Partnership conducts training at different levels. First, national or PA managers are trained to use SMART tools and data to support decision-making. Second, data analysts are trained to analyze and interpret SMART data and manage the SMART database. Lastly, rangers and local users are trained to use SMART for data collection in the field (R. Singh personal communication 11 February 2021).

Since its public release in 2013, SMART has already been used in over 765 PAs in more than 60 countries, of which around 14 countries have adopted SMART nationally. In the Asia-Pacific region, more than 400 PAs are using SMART in 18 countries.¹¹ Meanwhile, Bhutan, the Philippines, Thailand, and Vietnam have adopted it nationally (SMART Partnership 2018).

Results

Implementation

The national adoption of SMART means the government mandates its use in all PAs in the country. For instance, the forestry

departments of Bhutan¹² and the Philippines¹³ issued an order on the use of SMART in forest law enforcement and monitoring across their PAs. It is also embedded in their national strategies for PA management. In the Philippines and Thailand, SMART is part of the Landscape and Wildlife Indicator (LAWIN) Forest and Biodiversity Protection System and Smart Patrol System respectively (DENR 2018, WCS-Thailand 2021).

Thailand adopted SMART nationally in 2013 (SMART Partnership 2018). PA managers and conservationists in Thailand developed a system called the 'Smart Patrol System,' aiming at improving patrolling activities through science and technology (WCS-Thailand 2021). The Smart Patrol System uses the Network Centric Anti-Poaching System, which consists of various camera traps installed in the forest (Royal Thai Embassy 2019). It also uses SMART to conduct more effective patrolling and provide a database to store all the information gathered in the field (WCS-Thailand 2021). Every month, rangers must submit their SMART reports, which are then used to plan for the following month's patrolling activity (WCS-Thailand 2021).

In Bhutan, SMART was piloted in Royal Manas National Park (RMNP) in 2013 with the support of the World Wildlife Fund (WWF)-Bhutan. Seeing its success, the Ministry of Agriculture and Forests, Bhutan issued an Executive Order to implement SMART in all of Bhutan's PAs and territorial divisions (WWF-Bhutan 2016), affirming Bhutan's National Zero Poaching Strategy (WWF-Bhutan 2017). Subsequently, field staff from other PAs and government agencies were trained to use SMART (JSWNP 2016).

SMART was also launched in Vietnam in 2013. It was initially used in three sites under the 'Programme on Conservation and Sustainable

11 Afghanistan, Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Lao PDR, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Sri Lanka, Thailand, and Vietnam

12 See: <http://www.moaf.gov.bt/jswnp-implements-smart-patrolling/> and <http://www.dofps.gov.bt/>

13 See: <https://www.informea.org/sites/default/files/legislation/DENR%20Administrative%20Order%2021%202018%20%28Adoption%20of%20the%20Lawin%20Forest%20and%20Biodiversity%20Protection%20System%20as%20a%20National%20Strategy%29%20i.pdf>

Use of Forest Biodiversity and Ecosystem Services in Vietnam’ project of the Ministry of Agriculture and Rural Development and the German Corporation for International Cooperation GmbH (GIZ).¹⁴ After its successful implementation, its coverage was expanded to include seven more sites under the same project (SNRD Asia/Pacific 2016). Training was also done by the Carbon Sinks and Biodiversity Partnership (CarBi) in Thua Thien Hue Reserve (CarBi 2017). The United States Agency for International Development (USAID) Green Annamites Activity project¹⁵ supported SMART implementation in Song Thanh Nature Reserve, Elephant Habitat and Species Conservation Area, Ngoc Linh Nature Reserve, Phong Dien Nature Reserve, and Bac Hai Van Cultural and Historical Site. The project conducted capacity building for forest rangers, park area scientists, and technical staff. It also provided equipment such as laptops, printers, GPS, smartphones, and portable power banks in all PAs (ECODIT 2018). In 2016, the number of PAs using SMART in Vietnam increased to 26, and SMART was adopted nationally in 2017 (SMART Partnership 2018; Quang 2019).

SMART in the Philippines started in 2016 through the USAID-funded program on ‘Biodiversity and Watersheds Improved for Stronger Economy and Ecosystem Resilience’ (B+WISER)¹⁶. The B+WISER program developed the LAWIN Forest and Biodiversity Protection System,¹⁷ a PA management system that uses innovative technologies in forest monitoring (DENR-B+WISER 2017). SMART is used in LAWIN for data management and patrolling (DENR 2018). LAWIN was pilot-tested at the seven sites of the B+WISER program and was adopted as a national strategy for forest biodiversity protection in

the Philippines in 2018 (DENR-B+WISER 2017, DENR 2018). SMART is used at four levels: forest rangers and community members, resource managers, central office planners, and environmental law enforcers. The forest patrollers, composed of forest rangers and community members, collect data on threats, wildlife, and forest conditions in the field using SMART Mobile. The Response Protocol Manual (USAID and B+WISER 2018) guides them in determining the level of various threats in the area and how to act on those threats. The data collected are then uploaded to the SMART database, managed by data managers working in Environment and Natural Resource Offices (ENROs) at different levels: from the community (CENROs) to provincial (PENROs), regional (RENROs), and national levels (within the Department of Environment and Natural Resources (DENR) central office). The resource managers use SMART data at the local and national levels to support adaptive management in PAs. The central office uses the data to allocate resources to areas that need more assistance. Lastly, the environmental law enforcers, composed of national agencies and the DENR, use SMART to implement ecological laws (FMB 2016).

Site-specific implementations were also reported in other countries in the Asia-Pacific region. SMART is being used in Nam Et-Phou Louey National Protected Area, Lao PDR, through the support of Wildlife Conservation Society (WCS) Laos.¹⁸ SMART is used for patrolling and collecting data on wildlife, illegal forest activities, and threats. After every patrol, the data collected are stored in the SMART database at the park office. Every month, managers generate reports from SMART, assess the PA’s status, adjust their patrolling strategies, and improve their management to cover the threats identified (WCS-Laos and Nam Et-Phou Louey National Protected Area 2017).

SMART is also implemented in other forests in the region. SMART is used in the Sundarbans mangrove forest of Bangladesh through the Management of the Sundarbans Mangrove Forests for Biodiversity Conservation and

14 See: https://snrd-asia.org/download/conservation_and_sustainable_use_of_forest_biodiversity_and_ecosystem_services/Factsheet-Blo_EN.pdf

15 See: https://www.usaid.gov/sites/default/files/documents/FS_USAID_Green_Annamites_Nov2020_Eng.pdf

16 See: <https://www.usaid.gov/philippines/energy-and-environment/bwiser>

17 System named after the Philippine Hawk Eagle, locally called “Lawin”. See: <https://forestry.denr.gov.ph/index.php/lawin-forest-and-biodiversity-protection-system>

18 See: <https://laos.wcs.org/>

Increased Adaptation to Climate Change (SMP) project of the Ministry of Environment and Forests, Bangladesh, supported by the GIZ (SMP 2017). Pakistan has also started using SMART in 2017 to protect snow leopards in Khunjerab National Park, Central Karakorum National Park, and Margallah Hills National Park with the help of WWF-Pakistan (Jamal 2018).

Communities and the private sector also use SMART. SMART is used in participatory patrolling in Phong-Na-Ke Bang National Park in Vietnam. The Forest Protection Sub-Department and the Protection Forest Management Boards, together with local communities, conduct joint patrolling using SMART (Latham et al. 2014). SMART was also introduced to oil palm plantation, timber, and carbon storage and absorption companies in Indonesia in 2016, through the Provincial Green Growth Development¹⁹ program. At the end of 2018, two oil palm companies and four pulp and paper companies have adopted SMART (Hermawan et al. 2019).

These are a few among many examples of SMART use in 400 PAs in the Asia-Pacific region. They show that SMART can work in various environments and can also involve different stakeholders in forest conservation. However, despite its widespread implementation in the region, only four countries have adopted it nationally as of 2018.

Impacts

SMART has contributed to job creation and improved the skills of forest rangers, park staff, and government officers. The Philippines has 2,413 permanent forest rangers, 234 data managers, and 1,120 technical staff trained in SMART, and it has also increased its forest protection officers from 922 in 2016 to 1,023 in 2020 (FMB 2021). The Smart Patrol System in Kaeng Krachan National Park in Thailand provides annual training and courses on topographic map reading, identifying wildlife signs, and the use of GPS and SMART (WCS-

Thailand 2021). The SMART pilot testing in RMNP, Bhutan included 22 training sessions to train around 200 park staff from 2013 to 2015 (Dutta et al. 2015). In the Sundarbans in Bangladesh, 41 Forest Department staff were trained (SMP 2017).

With SMART data, patrolling routes are improved to cover a wider area and increase patrolling frequencies in areas facing high threats (CarBi 2017). Over the years, the number of patrols in Thailand has increased. In Umphang Wildlife Sanctuary, patrolling trips with 1 km² coverage have increased from 67 in 2010 to 69 in 2015 (WCS-Thailand 2021). In Thungyai Naresuan West Wildlife Sanctuary and Thungyai Naresuan East Wildlife Sanctuary, they increased from 28 and 12 patrolling trips in 2008 to 64 and 41 trips in 2015 respectively (WCS-Thailand 2021). In Huai Kha Khaeng Wildlife Sanctuary, patrolling trips increased from 36 in 2006 to 50 in 2015 (WCS-Thailand 2021). The same was also observed in Parsa National Park (PNP) in Nepal, where patrolling efforts doubled in less than a year (Cronin 2018).

Experiences with the use of SMART also show an improvement in the detection of illegal activities and threats. Forest rangers in Vietnam claim that SMART helps them identify and report illegal activities to local authorities. According to the rangers, identifying and reporting these illegal activities motivates them as they feel that their patrolling efforts are effective (Quang 2019). There has been a 90-percent reduction in the number of illegal activities since the patrollers started using SMART in PNP in Nepal (Cronin 2018). Similarly, from 2012 to 2017, the number of snares used to trap wild mammals in Phou Sithone Endangered Species Conservation Area in Lao PDR has decreased by 50 percent (WCS 2019).

SMART has played an essential role by providing information regarding the status of biodiversity. It can help in recording animal observations, and it also provides animal distribution maps. In Bhutan, SMART has recorded sightings of wild mammals (Letro 2016). However, it is difficult to attribute the improvement of biodiversity in the PAs to SMART alone as there are other conservation

¹⁹ See: <http://greengrowth.bappenas.go.id/en/about/>

projects in conjunction with SMART implementation.

SMART has also improved data management and reporting. Before implementing SMART, patrol data in the Philippines and Thailand were recorded using pen and paper, which could be easily lost or destroyed by rain (C. Pauig personal communication 2 February 2021; Mulqueeny and Cordon 2014). Similarly, in Vietnam, patrol data were manually recorded in a patrol diary and orally reported to PA managers. Forest rangers did not have GPS, binoculars, and cameras to properly document illegal activities in the forest. This affected the quality of data collected in the field and eventually affected decision-making for PA management (SNRD Asia/Pacific 2016). With SMART, many data can be collected, such as notes, GPS points, and photographs, which are essential evidence of illegal activities in the field (Mulqueeny and Cordon 2014). Furthermore, the SMART Partnership also trains data managers in data quality control (R. Singh personal communication 11 February 2021). This prevents transcription errors and data manipulation, which are otherwise common when data are collected through pen and paper. SMART cloud-based databases and standardized report formats help integrate data from different PAs. Thus, forest departments can quickly assess the status of different PAs and determine areas that need more assistance (DENR-B+WISER 2017, WCS-Thailand 2021). SMART also provides information, supporting the formulation of policies and projects at the national level (SNRD Asia/Pacific 2016).

Lastly, SMART has improved governance by promoting transparency and accountability. In a study conducted by Vimal et al. (2018), the interviewees claimed that SMART has improved forest rangers' performance. They observed that rangers are now actively patrolling the forest as their superintendents actively monitor them through patrol logs generated from SMART. SMART also improved the accountability of different SMART users in the Philippines (C. Pauig personal communication 2 February 2021).

Constraints

The SMART Partnership, supported by donor agencies, provides free software and training. However, the upscaling of SMART implementation is constrained by a lack of financial resources in the client countries. PAs need to bear the logistical costs of sending staff for training outside the state and for buying equipment such as smartphones and computers. Effective SMART implementation also requires increasing human resources such as data managers, technical staff, forest rangers, as well as personal protective equipment for the safety of field staff (Letro 2016).

Technical constraints such as slow internet connections are also a challenge for those implementing SMART Connect. The slow internet connection in the Philippines hinders the real-time synchronization of data from the field to the central database (C. Pauig personal communication 2 February 2021). Similarly, untimely transmission of data and inadequate battery capacity of devices were experienced during the roll-out of SMART in RMNP, Bhutan (Dutta et al. 2017).

There is also a need to increase training capacity. The SMART Partnership faces the challenge of scaling up its training capacity to cater to the increasing number of people interested in SMART (SMART Partnership 2018). Currently, the SMART Partnership is increasing its capacity by involving its country programs in training. The Partnership is also developing guided and self-guided online training to cover more participants, especially in pandemic times (SMART Partnership 2018).

Enabling environment

Experiences in Bhutan, the Philippines, Thailand, and Vietnam show that the national adoption of SMART requires pilot testing and training. The SMART Partnership delivers training for free to interested governments and agencies. The Partnership uses its resources to capacitate interested users and increase the adoption of SMART. The SMART Partnership is supported by its partners financially, and it also utilizes its

country programs to increase its capacity (SMART Partnership 2018). Governments and PAs bear the cost of sending their staff for training, but the pilot testing of SMART is usually integrated with conservation projects so that the project shoulders the costs. Thus, development institutions (e.g. USAID and GIZ) also play an important role by supporting conservation projects financially. NGOs other than the SMART Partnership can also help in delivering training and technical support. Further, the private sector can use SMART in its conservation areas or support conservation projects financially.

Government initiatives to upscale SMART implementation are necessary. Governments can support SMART by enforcing policies for its implementation in all PAs, as seen in Bhutan and the Philippines. They can also integrate SMART into their national PA management strategies, like in Thailand and the Philippines. Capacity-building should be strengthened so that more users can adopt SMART. There is high demand for SMART (SMART Partnership 2018), but the SMART Partnership cannot provide all of the required training alone. Collaboration with government agencies, international organizations, non-government organizations (NGOs), and the private sector is needed to deliver more training and scale up SMART implementation.

Governments should commit to adopting SMART nationally by allocating resources to its continuous implementation as conservation projects are not permanent. Further, SMART cannot solve the problem. It is just a tool that provides information and takes PA managers and governments into action. Thus, resources and commitment from PA managers and governments are needed to respond to the information provided by SMART.

Conclusions/wider implications of findings

Forest law enforcement and monitoring is a daunting task as it covers vast and remote areas. The lack of a system to record and store field data hampers adaptive forest management. Evidence from the countries reviewed in this study shows that free

and open-access tools like SMART have enhanced the efficiency of FLEG through improved patrolling, monitoring, and the identification of threats. SMART is already widely implemented in PAs in Asia-Pacific; however, only Bhutan, the Philippines, Thailand, and Vietnam have adopted it nationally. National adoption is encouraged to cover more PAs and to develop country-wide systems for enforcing forest laws and responding to threats and needs.

Governments and PA managers are already interested in SMART, given the increasing demand for training. However, its national uptake is constrained by a lack of funds and training. To increase SMART adoption in the region, it is suggested for governments, NGOs, development institutions, the SMART Partnership, PA managers, and the private sector to work together. Governments should include SMART in their national strategies for PA management and allocate resources to its continuous implementation. NGOs can support the SMART Partnership by providing training and capacity building for SMART implementation through conservation projects. Development institutions and the private sector can also contribute by providing financial support to conservation projects and the SMART Partnership to continuously improve the SMART software. PA management staff should implement SMART and upscale its use by joining training and capacity-building sessions.

Based on the new information generated from SMART, governments and PA managers should also accept changing their management and response to threats in their PAs. This may require more resources, including more personnel, better equipment (e.g., flashlights, firearms, and protective gear), greater funding, and the adoption of new practices that may require breaking conventional management. SMART is just a free tool supporting forest management, but translating its findings to adaptive management requires many resources and willingness from forest managers and government officials.

It is also essential to provide an avenue to share success stories and lessons learned

to encourage more users to adopt SMART, including through conferences, training and capacity-building programs. Research on the use of SMART is also highly recommended to evaluate and document its effectiveness. Very few studies on the use of SMART have been published in scientific journals. Most of the available information is from feature articles on NGO websites and project reports. To encourage research on the use of SMART, it is also necessary for governments and PA managers to be open to sharing SMART data for research and development purposes.

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UAV-derived forest degradation assessments for planning and monitoring forest ecosystem restoration: towards a forest degradation index

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Abstract

Global initiatives such as the Bonn Challenge and the New York Declaration on Forests have prompted large-scale forest restoration projects to combat land degradation, preserve biodiversity, improve local livelihoods and mitigate climate change. However, national and regional achievements to fulfill the quantitative targets set by these initiatives have been met largely outside natural forest areas, often in the form of conventional tree plantations, whilst degradation and deforestation continue in natural forests without much restoration being applied. Forest restoration in recently deforested sites can be achieved by nurturing natural regenerants and facilitating seed dispersal. This can result in more rapid carbon sequestration and biodiversity recovery compared to conventional tree plantations. Furthermore, many projects have been criticized for not matching restoration interventions with degradation levels. These insufficiencies have increased restoration costs while decreasing their effectiveness. Initial degradation assessment and restoration monitoring are essential for planning and managing restoration, but current surveys, which extrapolate degradation levels from small sample plots, are labor-intensive, expensive and inefficient. Meanwhile, drones and imaging technologies have become readily available and affordable and can rapidly cover entire restoration sites.

This study presents innovative techniques and tools using consumer-grade unmanned aerial vehicles (UAVs or drones) and imaging technologies, which offer a rapid and cost-effective way to collect data, enabling stakeholders to assess initial degradation levels, develop restoration plans, and monitor restoration progresses. Such data could be used to further develop a forest-degradation index (FDI) for restoration sites.

To test the applicability and reliability of UAV-derived RGB imagery, a pilot study was conducted in Tum Pha Thai National Park, Northern Thailand. RGB images were captured using a consumer-grade quadcopter (DJI Phantom 4 Pro) with an onboard camera. The images were processed

using the WebODM Lightening platform, generating a digital surface model, a digital terrain model and an orthophoto. An algorithm-based R package (ForestTools), and a deep learning-based platform (Picterra) were used to detect forest attributes. The strengths and weaknesses of the two tools are discussed.

Keywords: *Climate change, Deforestation and forest degradation, Monitoring and data collection, Unmanned aerial vehicles, Forest-degradation index.*

Introduction and background

Forest ecosystem restoration is being widely implemented to combat land degradation, preserve biodiversity, improve local livelihoods, and mitigate climate change. The importance and the urgency of the task have been demonstrated globally through various organizations and agreements, such as Aichi Target 15 of the UN Convention on Biological Diversity (CBD 2002, 2010)¹, the Land Degradation Neutrality Target of the UN Convention to Combat Desertification (UNCCD)², the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program³ of the UN Framework Convention on Climate Change (UNFCCC 2008), and the UN Decade on Ecosystem Restoration (2021–2030).⁴ Ambitious restoration targets have also been proposed by global initiatives such as the Bonn Challenge⁵ and the New York Declaration on Forests (NYDF)⁶: 150 million hectares by 2020, and 350 million hectares by 2030. In the Asia-Pacific region, the Asia-Pacific Economic Cooperation (APEC) launched the APEC 2020 Forest Cover Goal in 2007, aiming to increase forest cover to 20 million hectares by 2020 (APEC Economic Leaders 2007; FAO 2019). FAO and the Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet) also developed the Asia-Pacific Regional Strategy and Action

Plan for Forest Landscape Restoration to 2030 (FAO and APFNet 2018).

Shortcomings of efforts to restore forest ecosystems

Such ambitious targets have been criticized. The first issue is: where to restore forests? Most restoration projects pledged under the Bonn Challenge and NYDF have been implemented outside natural forest areas, often in the form of conventional tree plantations, whilst degradation and deforestation in natural forests have continued (NYDF Assessment Partners, 2019; Lewis et al. 2019). Forest ecosystem restoration should be implemented where forests have been recently destroyed or degraded (Di Sacco et al. 2021). Most such areas are close to or connected with remnant forests. It is important to identify and select these sites because restoration can rapidly recover biomass (and carbon), structural complexity, biodiversity, and ecological functioning to reference forest levels (Aerts et al. 2011; Elliott et al. 2013; Stanturf et al. 2014; Lewis et al. 2019; Di Sacco et al. 2021).

Another issue is a poor understanding of the initial conditions of given sites (i.e. the lack of initial assessment of forest degradation). Inadequate site assessment and monitoring can result in project failure. Zhai et al. (2014) reported a lack of distinction in forest quality: for instance, projects on Hainan island, China, defined plantations as “natural forests” and natural shrublands and grasslands as “bare hills” according to government policy, resulting in an expansion of deforestation and plantations in the name of restoration. Furthermore, Thomas et al. (2015) highlighted that selecting tree species

1 See: <https://www.cbd.int/sp/targets/>

2 See: <https://www.unccd.int/actions/achieving-land-degradation-neutrality>

3 See: <https://redd.unfccc.int/>

4 See: <https://www.decadeonrestoration.org/>

5 See: <http://www.bonnchallenge.org>

6 See: <http://forestdeclaration.org>

that are not adapted to local site conditions can lead to low germination and survival rates. Other interventions (e.g. weed control, seed sourcing, nutrient application and the production of healthy planting stock) can also determine the success or failure of restoration projects (Poopathy et al. 2005). A wide range of forest restoration methods are available to address a spectrum of degradation levels (i.e. from no-intervention, protection, and assisted natural regeneration to applying framework species,⁷ maximum-diverse species,⁸ and nurse plantation methods⁹) (for more information, see Elliott et al. 2013). Consequently, assessing the initial level of degradation is essential so that suitable interventions at appropriate levels of intensity can be applied. It is important to monitor changes in degradation level following interventions to assess the effectiveness of each restoration method in a given restoration site.

Currently, ground-based surveys are used to assess forest degradation and monitor restoration progress. Sample plots are laid out across the site and the number (density), size and species of trees are recorded along with site conditions (e.g. dominance of weeds, quality of soil, evidence of soil erosion, fire, and pasture). Such surveys are labor- and cost-intensive and prone to errors due to inadequate sampling. To overcome these constraints, this study explored techniques to perform site assessments and restoration monitoring from the air using a consumer-grade UAV (or drone) to generate data for the development of a forest degradation index (FDI).

Description of the innovation

Remote sensing, surveying forests and detecting the level of forest degradation

Remote sensing (RS) – data collection using various platforms and sensors without physical contact with objects – has been widely used to survey forests. For example, satellite imagery has been used for more than 20 years (Alonzo et al. 2018; Camarretta et al. 2020). Such data, periodically collected over long time spans and over wide spatial scales, have allowed the identification of land cover and detection of land use changes (Miranda et al. 2020), including changes in forest cover and condition, due to selective logging or fire (Shimabukuro et al. 2014). However the resolution of satellite images is not high enough to be useful for site-level planning and management (Da Ponte et al. 2017; Alonzo et al. 2018), nor for the quantitative detection of forest attributes and composition (Miranda et al. 2020).

Aircraft, particularly UAVs, can fly close to targets at low cost and generate very high-resolution images (Alonzo et al. 2018; Camarretta et al. 2019). In particular, light detection and ranging (LiDAR) – based on emitted laser light reflected back from objects – is now being widely used to survey forests. A LiDAR sensor mounted on a UAV can detect tree density, height, crown diameter, overall canopy cover, gap fraction,¹⁰ canopy Shannon index¹¹, leaf area index (LAI)¹² and biomass stock (Mutwiri et al. 2017; Sankey et al. 2017; De Almeida et al. 2019, 2020). Such data can be integrated with Landsat

7 The framework species method is the least intensive of the tree planting options: it exploits natural seed dispersal mechanisms to obtain the number of trees necessary to shade out weeds and attract seed-dispersing animals.

8 The maximum-diverse species method involves recreating the tree species composition near to the original diversity through intensive planting. It is recommended when seed dispersal is limited from remnant forest (e.g. long distance to seed trees and lack of seed-dispersing animals).

9 The nurse plantation method involves planting highly resilient tree species to improve the soil and modify the micro-climate.

10 The gap fraction is a proportion of area with lower canopy height than the threshold defined for a gap (Brokaw 1985). It reflects the history of tree mortality and influences the light environment and leaf area (Stark et al. 2012).

11 The Shannon Index can be used to quantify the structural diversity of tree canopies, as reflected by the leaf area density. It is expected to be correlated with the taxonomic biodiversity of trees in the plot (Stark et al. 2012).

12 The leaf area index (LAI) is a basis to estimate variation in vegetation density from optical transmission rates and represents the area of leaves per unit of ground area (De Almeida et al. 2019; 2020).

satellite data (Caughlin et al. 2016) and hyperspectral or multispectral data from UAVs (Sankey et al. 2017) to produce highly detailed 3D forest models and orthorectified maps. However, LiDAR units for UAVs are very expensive, unaffordable to stakeholders of small-scale restoration projects such as non-governmental organizations (NGOs) and community-based groups, particularly in low-income countries.

Structure from motion (SfM) technology, using RGB photographs¹³ from onboard drone cameras, is a more affordable way to create 3D forest models and maps. It works by parallax – close objects appearing to move past an aircraft faster than more distant objects. The technology constructs a 3D point cloud model¹⁴ by repeatedly detecting the same point in multiple photographs taken from a drone-mounted camera whilst flying over the site in a grid pattern¹⁵ (Ullman 1979; Shapiro and Stockman 2001). Such 3D models have been used to detect tree tops and tree crown boundaries, as well as measure stocking density, tree height, canopy cover, crown openness, diameter at breast height (DBH), above-ground biomass (AGB), assess carbon stocks; even tree species identification has been attempted (Zahawi et al. 2015; Fujimoto et al. 2019). The accuracy of such measurements is tested against ground-survey data and/or LiDAR data (Khokthong et al. 2019; Swinfield et al. 2019).

Available tools processing UAV-derived RGB photographs

Processing RGB images for SfM can be done with various paid or open-source software (e.g. Metashape,¹⁶ Pix4D, DroneDeploy, OpenDroneMap). These programs process sets of airborne RGB images to generate 3D point clouds, digital surface models (DSMs), digital terrain models (DTMs) and orthophotos (flat maps). DSMs and DTMs are two types of digital elevation models (DEMs) in raster format.¹⁷ DTMs present the ground elevation whilst DSMs present the upper surface of objects (e.g. forest canopy). Therefore, the height of a forest canopy above ground (crown height model, CHM) is derived by subtracting DSM elevations from DTM elevations. Orthophotos are mapped (georeferenced) 2D images generated from the 3D mesh¹⁸ with radial distortion corrected (**Figure 1**).

The analysis of raw RGB images can also yield useful data. For example, some of the more distinctive tree species can be distinguished using the color-threshold function in ImageJ¹⁹ to adjust image hue, saturation and brightness (HSB).²⁰ However, the use of raw images has flaws, such as radial distortion (objects towards the edges of images appearing tilted) and pixels of several tree species and even ground vegetation sharing similar properties. Orthophotos can address the issue of radial distortion, and CHMs can distinguish between ground weeds and forest canopy by height. However, the resolution of orthophotos and CHMs is much

13 In RGB images, red, green, and blue light are added together in various proportions to reproduce a broad array of colors. Conversely, each color can be decomposed and coded using its three red, green and blue components.

14 A point cloud model is a set of data points, each associated with its spatial coordinates, representing a 3D shape or object.

15 Common grid patterns included in most drone apps are: (i) the single grid pattern; (ii) the double grid pattern; and, (iii) the circular pattern. Different patterns are best adapted to different objectives. See for instance: <https://support.pix4d.com/hc/en-us/articles/209960726-Types-of-mission-Which-type-of-mission-to-choose>

16 See: <https://www.agisoft.com/>

17 A raster is a grid of pixels identified with their coordinates (x, y, and z), information (e.g. their latitude and longitude), and elevation above sea level.

18 A 3D-mesh model consists of triangle-shaped meshes, polygonised with major points from point cloud. It presents more distinct boundaries over objects compared to raster formats.

19 See: <https://imagej.nih.gov/ij/>

20 HSB is a color model, identifying colors with three elements: a particular wavelength in visible rays (hue), percentage of purity of color (saturation; 0% is pale and 100% is pure and strong), and percentage of whiteness (brightness; 0% is black and 100% is white).

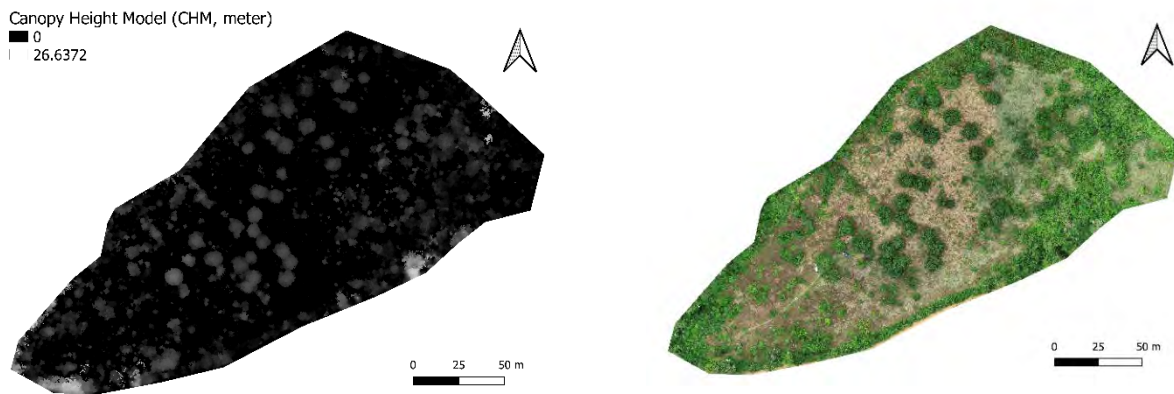


Figure 1: (Left) Canopy height model (CHM), where the height of each pixel is expressed in grey-scale, from black: 0m (lowest, ground), to white: 26m (highest). (Right) Orthophoto, color 2D map, in which overall RGB images are aggregated.

Source: Author

lower than that of raw images, since they are based on point clouds.

Algorithm-based tools can be used to detect tree top points and delineate tree crown boundaries from CHMs, such as an R package algorithm, ForestTools²¹ (Plowright 2020) and a Python package algorithm, PyCrown²² (Zörner et al. 2018). Tree top points can be used to derive stocking density and height, and tree crown boundaries can be used to estimate the crown area of individual trees and the percentage of canopy cover. AGB and carbon stock can also be derived using allometric equations²³ (Zahawi et al. 2015; Jucker et al. 2018; Fujimoto et al. 2019). Another Python package, DeepForest²⁴ (Weinstein et al. 2020) is based on deep learning.²⁵ The package includes a pre-trained model based on RGB imagery from six forest types to generate tree crowns. This reduces the need for a lot of training

21 See: <https://pypi.org/project/foresttools/>

22 See: <https://opensourcelibs.com/lib/pycrown>

23 Allometry, also called biological scaling, studies the changes occurring in organisms in relation to size, i.e., the relationships between size, shape, anatomy, physiology and behavior.

24 See: <https://deepforest.readthedocs.io/en/latest/landing.html>

25 Deep learning, or deep structured learning, is a form of machine learning in which multi-layered artificial neural networks – modeled to work like the human brain – 'learn' from large amounts of data.

data (RGB forest imagery), allowing users to directly process their UAV-derived RGB images. Another groundbreaking tool, Picterra, provides a user-friendly interfaced platform allowing users to train the detector using their own spaceborne or airborne images by hand-drawing polygons (boundaries) of objects, without requiring any coding or AI expertise (Picterra 2018).

Results and discussion

Pilot study in Tum Pha Thai National Park in northern Thailand

A pilot study was conducted in Tum Pha Thai National Park in northern Thailand to (i) test the detection of forest attributes using UAV-derived RGB imagery, and (ii) compare accuracy across tools. The study site (3 hectares) had been illegally deforested and subsequently replanted with indigenous forest tree species in 2018. Weeding and fertilizer application were performed for 3 years. Aerial RGB images were collected 50 m above ground in June 2020 using a consumer-grade quadcopter UAV (DJI Phantom 4 Pro²⁶) with an onboard RGB

26 Phantom is the name of a series of UAV by DJI, a Chinese technology company. See: <https://www.dji.com/it/phantom-4>

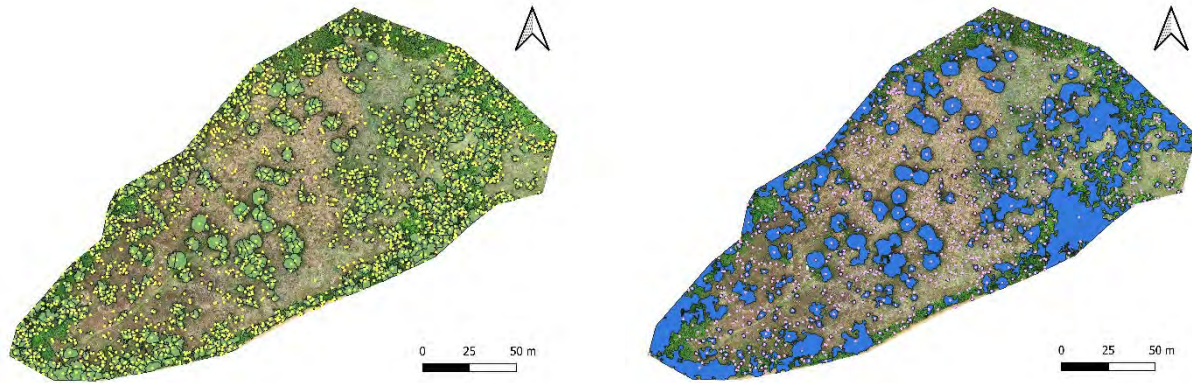


Figure 2: Comparison between ForestTools from CHM (left, yellow points=tree-tops, green polygons=tree crowns) and Picterra by deep learning from the orthophoto (right, pink points=tree-tops and blue polygons=tree-crowns)

Source: Author

camera (1-inch 20-megapixel CMOS sensor).²⁷ Images were processed using the WebODM Lightning platform, generating a DSM, a DTM and an orthophoto. Tree top detection and tree crown delineation were performed with two tools: (i) the R package algorithm ForestTools, using the CHM; and (ii) the deep learning-based platform Picterra, using the orthophoto (**Figure 2**). The numbers of trees detected with both tools were compared with those detected by eye by hand-drawing on the images.

The stocking density, derived from the computer models, was compared with that estimated visually in 10 circular sample plots (5 m radius, used for the ground survey) (Table 1). ForestTools underestimated tree numbers in the CHM in seven of the 10 plots (omission error, -3.57 (mean) \pm 0.78 (SD)). Picterra also underestimated tree numbers in seven plots (-2.14 (mean) \pm 1.07 (SD) and overestimated them in two.

Strengths and weaknesses of the tools are compared below (**Figures 3 to 5**). However, it should be noted that weaknesses might be overcome by better calibrating the tools, such as by setting different equations and minimum tree heights in the R package algorithm, or by adding training data to the deep learning-based platform.

²⁷ Complementary metal–oxide–semiconductor (CMOS) active pixel sensor. See: https://en.wikipedia.org/wiki/Active-pixel_sensor

Discussion of the pilot study

Large crowns and edge-touching crowns

As illustrated in **Figure 3**, ForestTools often detected several tree top points within single large tree crowns. On the other hand, Picterra was successful at distinguishing tree crowns only when the trees were distinctively separated; edge-touching large crowns were often recognized as single trees.

Small trees

As illustrated in **Figure 4**, ForestTools often failed to detect small trees in the CHM. This was because the algorithm is based on point heights in the CHM. The minimum tree height can be set by the user, but when it is set too low, other weeds and debris (higher than the given height) are treated as trees. Conversely, when the minimum height is set too high, small trees cannot be detected. In this pilot study, the minimum height was set to 1.0 m. In contrast, tree detection with deep learning using the orthophoto is based on training images provided to the system by the user. Therefore, if users include small trees in the training images, the detector will recognize them. Small trees can be more successfully detected when the background color is very different from that of the tree crowns (e.g. dry grass or soil).

Distinguishing weeds and trees

Table 1: Ten circular sample plots were compared for the number of detected trees. Hand-drawing is the reference, CHM detection, and deep learning detection were compared: cor=correlation coefficient, RSME=root mean square error.

Sample plot	Hand-drawing	CHMs detection	Deep learning detection
1	3	3 (0)	4 (+1)
2	10	6 (-4)	8 (-2)
3	3	0 (-3)	4 (+1)
4	10	7 (-3)	6 (-4)
5	4	4 (0)	3 (-1)
6	10	7 (-3)	8 (-2)
7	5	5 (0)	4 (-1)
8	10	6 (-4)	7 (-3)
9	4	1 (-3)	2 (-2)
10	6	1 (-5)	6 (0)
<i>cor</i>		<i>0.81</i>	<i>0.88</i>
<i>RMSE</i>		<i>3.05</i>	<i>2.02</i>
<i>R²</i>		<i>0.6561</i>	<i>0.7716</i>

It is often difficult to visually distinguish tree crowns from dense, green weed cover in RGB images since their colors are similar. ForestTools was able to detect several small trees using height differences in the CHM instead of color. However, as mentioned above, when heights of weeds are similar to or taller than those of small trees, ForestTools is also limited in its ability to detect those trees. On the other hand, Picterra was less efficient at distinguishing between green weeds and tree crowns in the 2D orthophoto as shown in **Figure 5**.

Constraints and challenges

One limitation of using RGB imagery to generate CHMs is that many small trees are invisible beneath the crowns of larger trees, whereas LiDAR can “see through” the forest canopy to a certain extent. This problem is evident both with computer tools and with hand drawing, using 2D orthophotos and raw RGB images. Although this barrier is inevitable

when using RGB imagery, it is still possible to evaluate the canopy cover and tree height of most trees. Furthermore, it may be possible to develop models to predict the number of undetected trees by relating tree-size frequency distributions in the target forest with other variables such as percentage canopy cover.

A lack of capacity among project stakeholders may present another barrier to the wider use of drones for planning and monitoring forest restoration. Although consumer-grade UAVs with RGB cameras are cheaper than LiDAR-mounted UAVs, initial costs would still be high for most small NGOs and community groups. In addition to the drone itself, other items must be purchased including a tablet or mobile device for control, extra batteries, software licenses, and mobile internet. The learning curve to operate drones and process images is steep, and training of local stakeholders is needed, possibly incurring additional costs. Simply flying drones and recording images is not very difficult, but

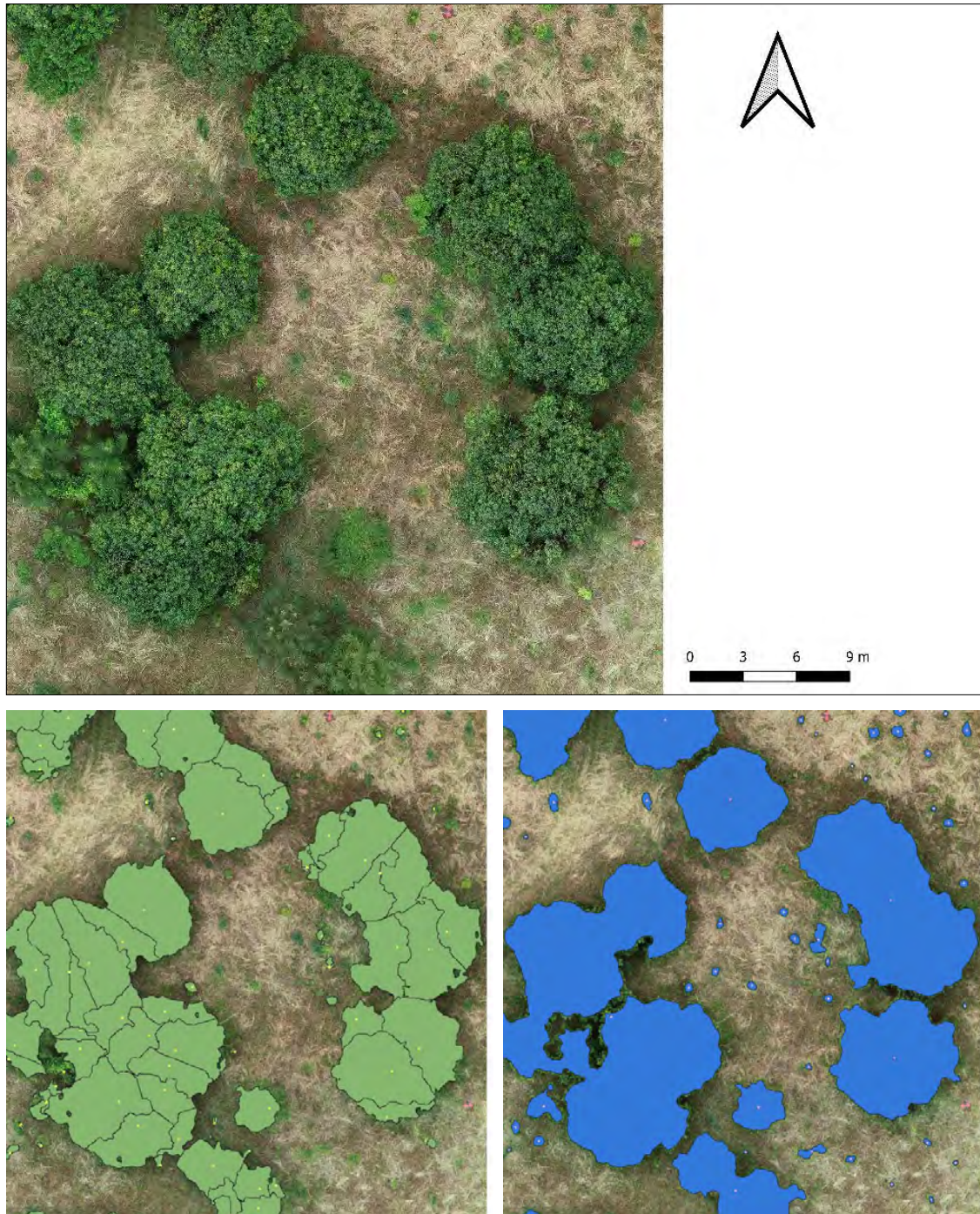


Figure 3: (top) Orthophoto for reference. (Left) Algorithm-based R package (ForestTools), detecting large crowns as several trees. (Right) Deep learning-based platform (Picterra); adjoining crowns detected as a single tree.

Source: Author

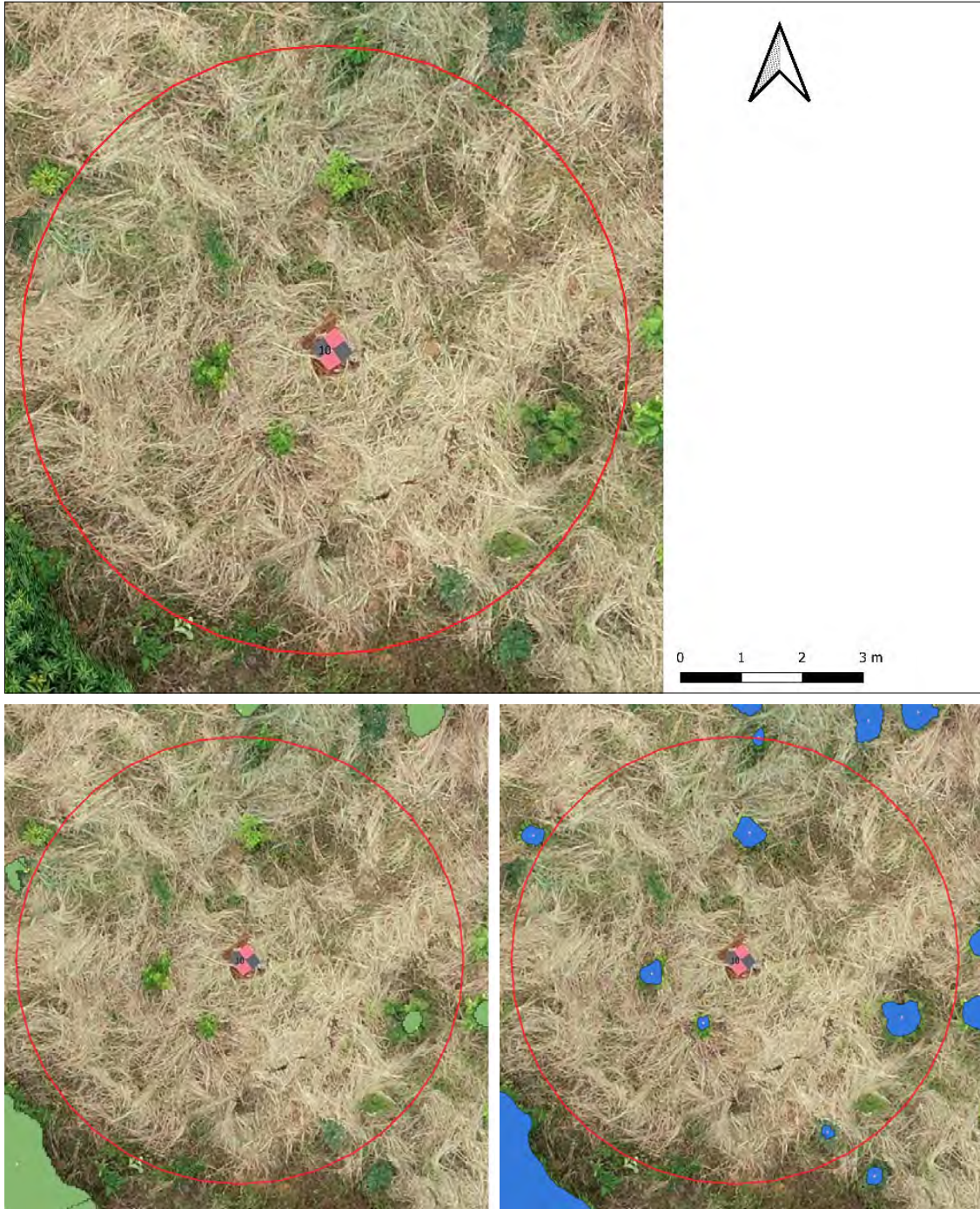


Figure 4: (top) Orthophoto for reference; six small trees are observed in the red circular sample plot. (Left) Algorithm-based R package (ForestTools); only one tree is detected. (Right) Deep learning-based platform (Picterra); all six trees are detected.

Source: Author



Figure 5: (top) Orthophoto for reference; human eyes can hardly find the small trees emerging above the weed cover (Left) Algorithm-based R package (ForestTools); several trees are detected. (Right) Deep learning-based platform (Picterra); only two trees are detected.

Source: Author

doing so to collect high-quality images for the processing and construction of CHMs and 3D models requires considerable technical expertise and knowledge about how SfM works (e.g. matching aircraft speed with camera settings, designing flight missions to cover the site adequately within limited battery life, safety and weather issues, etc.). Training by specialists is usually necessary.

However, using the types of data presented in this paper may save time and money in the long run and would certainly facilitate restoration planning and monitoring. Many people are needed for ground surveys. For the rapid site assessment of one small restoration project in northern Thailand, on about 0.5–3.0 hectares, at least three to four teams of two to three members each are needed to adequately sample data in a day. The surveyors require transport, food and salary payments. Costs are related to the number of people involved and to the area of the restoration site. On the other hand, over the same area, a single team of three people working for a few hours is sufficient for drone flying. Operational costs are therefore lower compared with ground surveys, although initial costs are considerably higher.

Using UAV-derived parameters to develop a forest-degradation index (FDI)

It is often confusing to consider individually multiple variables and this hinders communication. Creating a single index to describe a complex state can make its assessment more easily understood by the general public (United States Environmental Protection Agency 2014). An index is a dimensionless cardinal number derived by integrating several variables. Such indices have been used to quantify environmental risk and the severity of disturbances, such as air quality, water quality, and health risk indices. A further development would be to synthesize the data presented in this study into an index representing the vegetation that could illustrate the severity of degradation and the potential effectiveness of restoration interventions in a specific area. Such an index would be easily communicated and understood, whilst retaining a logical scientific basis. Therefore clear, simple and reliable

index numbers could provide a decision-support tool to planners and policymakers as to where to implement restoration and could be used to gain support from donors and other stakeholders.

Conclusion

While global initiatives are based on quantitative goals (e.g. numbers of trees and size of areas planted), the quality of restoration work is often overlooked (e.g. selecting more effective sites and intervention, managing properly planted trees to increase the survival rate). This can lead to the failure of restoration projects and even accelerate the deforestation and degradation of natural forests (NYDF Assessment Partners 2019; Lewis et al. 2019; Di Sacco et al. 2021).

Therefore, this study emphasizes the appropriate assessment of forest degradation and monitoring of restoration progress as a solution to current problems. It introduces innovative techniques and tools using consumer-grade UAVs to do so. The pilot study at Tum Pha Thai National Park tested two tools and identified their relative strengths and weaknesses. Although further refinement of such tools may be needed, the pilot study demonstrated the potential for consumer-grade UAVs to detect parameters describing forest degradation and the effectiveness of restoration.

Furthermore, their use for developing a forest degradation index (FDI) based on UAV-derived data would support decision-making when planning restoration and subsequent monitoring, thus enabling restoration projects to be assessed in terms of their quality, numbers of trees planted and size of restored sites.

A FDI may not be a perfect solution, and using UAV-acquired images may not be as precise as measuring every tree on the ground. However, the reduced precision of drone-derived data must be considered against the reduced operating costs of drone surveys and the fact that drones can cover

entire sites, whereas sample plots cover only a tiny percentage. Therefore, institutions that facilitate and support forest restoration should consider providing training in UAV flying and photogrammetric techniques to stakeholders involved in restoration projects. These recommendations are in line with the need to increase technical capacity, as identified by the UN Decade on Ecosystem Restoration 2021–2030.

Acknowledgements

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Estimating tree height, canopy cover, and tree diameter with unmanned aerial vehicle (UAV) technology

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Abstract

Forest inventory is used to collect data and information about a forest and to manage it for the future. It notably measures tree height, canopy cover, and tree diameter. These data are used to measure the availability of forest resources and ecosystem services, including wildlife. Data on tree height and diameter can be used to estimate above-ground biomass and carbon stock in the forest. Canopy cover data can be used to predict forest capacity to serve as habitat for arboreal animal wildlife.

Many inventory activities are conducted manually because of limited access to technology. Unmanned aerial vehicles (UAVs) could be used to support inventory activities, but models estimating tree height, canopy cover, and tree diameter are needed to facilitate the inventory. The purpose of this study is to generate a model based on UAV data, estimating tree height, canopy cover, and tree diameter for teak trees of varied age classes (AC) in the Ciamis Forest Management Unit, West Java, Indonesia.

Keywords: *Canopy Cover, Estimating Diameter, Estimating Height, Management Forest, Modeling, UAV*

Introduction and background

Forest inventory aims at collecting information about a stand's structure, composition, and potential, serving as the basis for forest management (Putra 2015). Among the parameters measured in forest inventory are tree height, canopy cover, and tree diameter. Data on tree height and diameter at breast height (DBH) can be used to estimate above-ground biomass and carbon stock (Hashem 2019). Canopy cover information is used to estimate other ecosystem services, such as climate regulation, wildlife habitat, and emissions of organic compounds that can facilitate cloud formation (Ozanne et al. 2003). Canopy cover data is essential to monitor global changes that include climate change and land conversion that causes habitat loss. Tree canopies bring a lot of benefits for wildlife, such as shelter, cover, and places to find food and breed, especially for arboreal animals¹. If habitat fragmentation occurs in a forest area, it affects the existence and sustainability of wildlife. Canopy cover measurements are useful in determining the forests' potential as habitat for arboreal animals.

The estimation of tree height, canopy cover, and tree diameter has been performed in several prior studies using remote sensing and geographical information systems (GIS). Unmanned aerial vehicles (UAVs), also known as drones, are expected to be more effective and efficient at estimating these stand parameters. Birdal et al. (2017), for instance, used drones to estimate tree height in the urban forest of Eskişehir, Turkey. They showed the effectiveness of drone technology that generates highly accurate data while reducing ground checking. Using drones can facilitate forest inventory and reduce its cost. Strigul et al. (2015) stated that modern drones, equipped with affordable camera rack, panchromatic camera, and/or flexible camera, are an economical alternative for collecting inventory data.

1 Arboreal animals are wild animals living in tree canopies and from tree canopy resources (Suprianta and Ramadhan 2016; Mustari 2019).

This study was conducted within the Ciamis Forest Management Unit (West Java, Indonesia), in two locations as illustrated in **Figure 1**:

- South-Banjar (Sector Pamarican), representing Age Class IV (AC4), i.e., 16–20-year-old forest stands; and,
- Pangandaran (Sector Sidamulih), representing 26–30-year-old and 36–40-year-old forest stands, respectively Age Classes VI and VIII (AC6 and AC8).

The purpose of this study is to generate a model based on UAV data, estimating tree height, canopy cover, and tree diameter for teak trees of varied age classes (AC) in Ciamis Forest Management Unit (West Java, Indonesia). This study will help define the most effective flying altitude for UAVs to collect high-quality data on each age class in the Ciamis Forest Management Unit.

Method

This study is divided into four steps: (1) UAV flight and image acquisition, (2) UAV image processing, (3) data analysis and (4) estimation of field time – presented in the following sections.

UAV flight and image acquisition

UAV cameras can take pictures, then used to estimate tree height, canopy cover, and tree diameter. The following actions were performed before the UAV flight: (i) pre-mark installation in an area of interest (AOI) (i.e., physical marking of ground control points (GCPs));² and (ii) flight path creation with the DroneDeploy software.³

Images and data were collected directly with a drone (DJI Phantom 4 Quadcopter) flying at an altitude of 100 meters. The images and data were calibrated by flying the drone over open land in each AC (see

2 Ground control points are points made physically visible on the ground, with known geographical coordinates. They facilitate the accurate mapping of large areas, using aerial imagery.

3 See: <https://www.dronedeploy.com/>

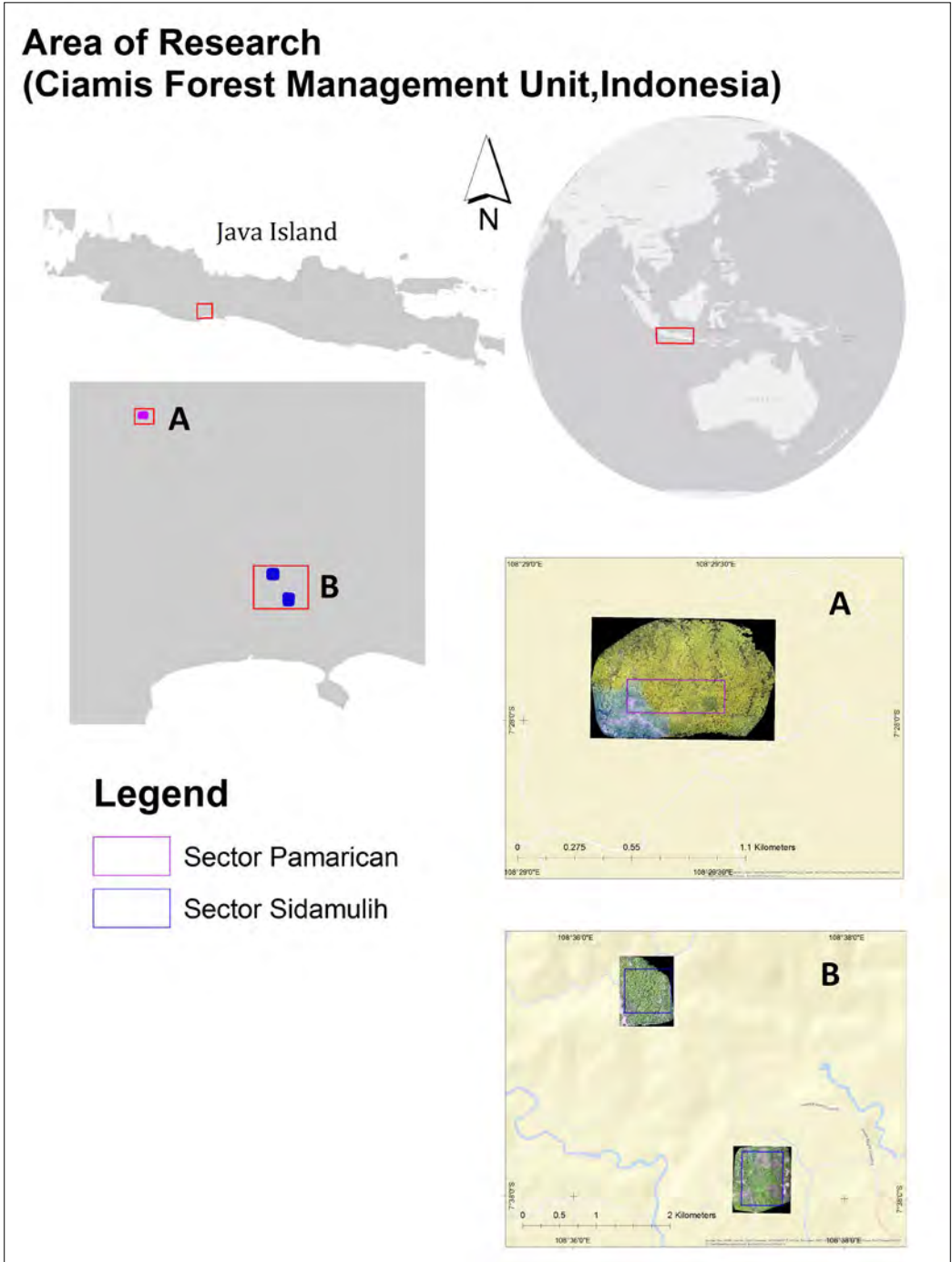


Figure 1. Area of research in the Ciamis Forest Management Unit, Indonesia. The Sector Pamarican (A) contains 16–20-year-old teak-tree forest stands. The Sector Sidamulih (B) contains 26–30-year-old and 36–40-year-old teak-tree forest stands.

Source: Authors

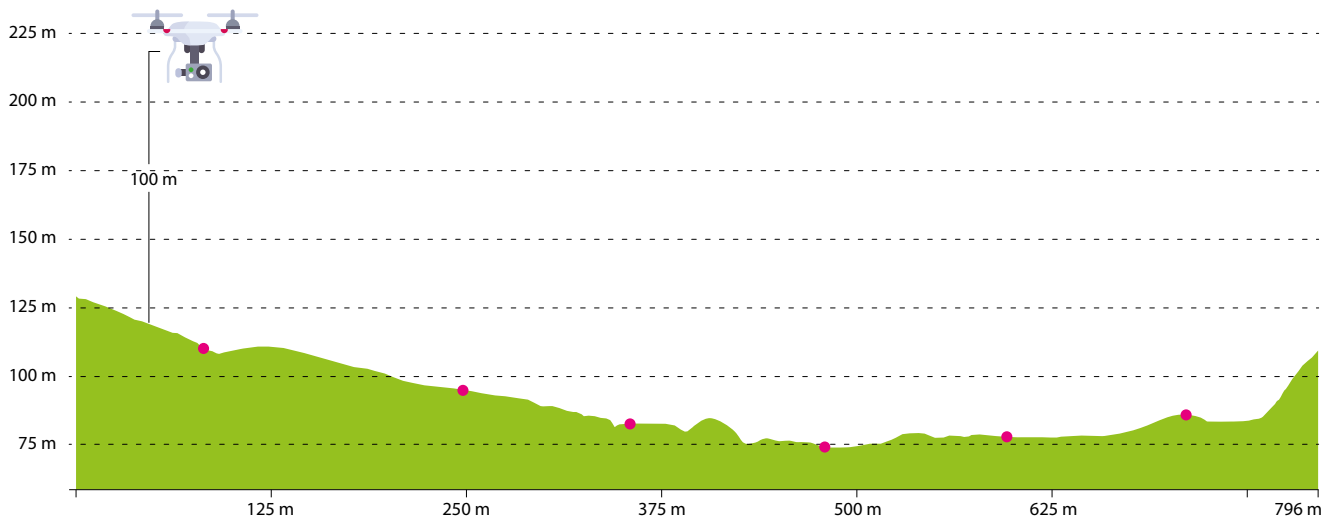


Figure 2. Illustration of flying drone

Source: Authors

Figure 2). The objective was to keep the signal between the drone and the control steady so that the image result is not corrupted during processing. Overlap and sidelap⁴ were adjusted respectively to 80 percent and 70 percent to ensure high-quality photogrammetry (Zulkipli and Tahar 2018). The camera was pointing in the nadir direction (90°)⁵ with a single grid pattern.⁶ The single grid pattern was chosen because the camera was perpendicular to the AOI, so a single shot was enough during the aerial

4 The drone flies back and forth to cover the whole area of interest, dividing it in parallel lanes. “Overlap”, “frontlap” or “forward overlap” denote the proportion of common content in two adjacent photos taken in the same lane, while “sidelap” or “lateral overlap” denotes the proportion of common content in two photos taken in adjacent lanes. Lower overlap and sidelap means higher productivity and reduced costs, while higher overlap and sidelap are associated with higher image quality. Typical sidelap and overlap requirements can range from 60 to 75 percent, depending on the end-use of the image acquired. See: <https://sentera.com/6x-why-capture-rate-matters/> or <https://www.aerotax.com/overlap-flight-pattern>

5 The nadir at a given point is the local vertical direction pointing downwards, i.e., following the direction of the gravity force in that location.

6 The more common flight missions included in most drone apps are: (i) the single grid pattern; (ii) the double grid pattern; and, (iii) the circular pattern. For more information on the different flight missions best adapted to different objectives, see for instance: <https://support.pix4d.com/hc/en-us/articles/209960726-Types-of-mission-Which-type-of-mission-to-choose>

photography. Tree sampling was performed on each AOI on 30 trees to calibrate the model. The tree height measurement was carried out using a Leica Disto Touch D810 laser distance meter,⁷ and the DBH was calculated with a push-broom hyperspectral imager band.⁸

The GCP benchmark data was measured with a *Trimble R8s* satellite navigation receiver⁹. Such dual frequency geodetic global positioning systems provide more accurate and precise coordinate information, i.e. with an error score level around a centimeter (Gerke and Przybilla 2016). The GCP data is used to calibrate UAV images and to enhance mapping accuracy.

UAV image processing

Data processing and analysis went through three stages as shown in **Figure 3**.

The UAV aerial photography image went through a three-stage process. At stage 1, the UAV image was processed with the Pix4D

7 See: <https://leica-geosystems.com/products/disto-and-leica-lino/leica-disto/leica-disto-d810-touch>

8 For more information, see for instance Tong et al. (2014), or: https://en.wikipedia.org/wiki/Hyperspectral_imaging

9 See: <https://geospatial.trimble.com/products-and-solutions/trimble-r8s>

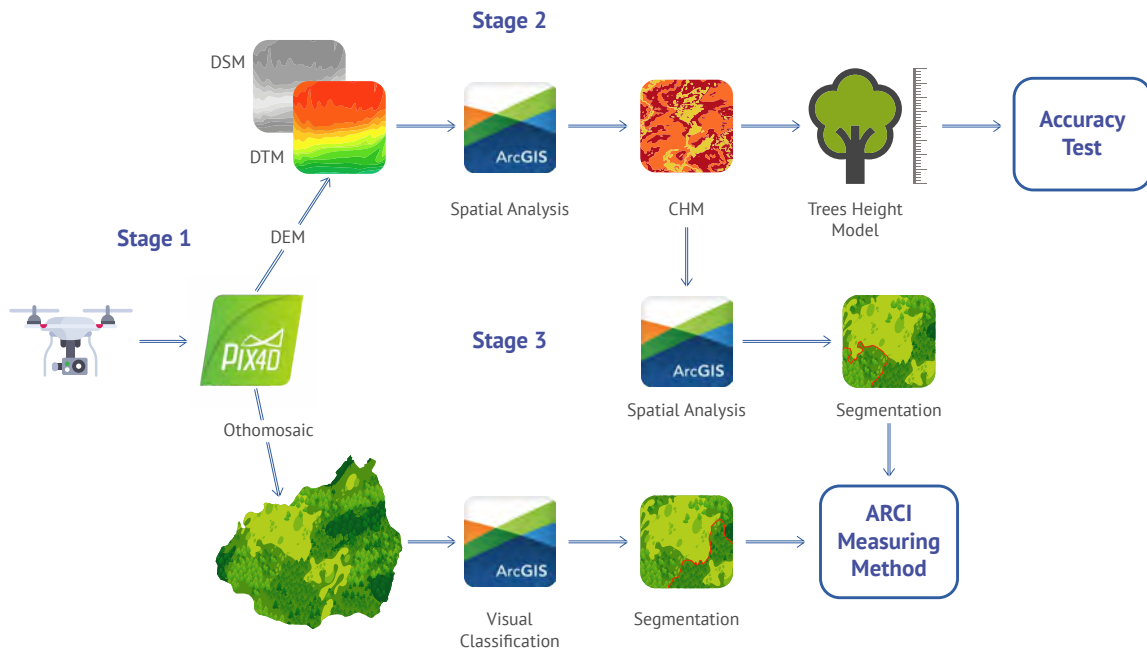


Figure 3. Data processing and analysis

Source: Authors

Mapper software¹⁰ to produce georeferenced orthoimages as well as a digital elevation model (DEM)¹¹ (Zhang et al. 2016).

At stage 2, data resulting from stage 1, formatted as DEM data, were used to derive a digital surface model (DSM) representing the Earth's surface, including all above-ground features such as buildings or canopy cover, and a digital terrain model (DTM) representing the ground level without the above-ground objects. Both data were analyzed spatially using the ArcMap 10.5 software¹². DSM and DTM data, in raster¹³ format, served as basic inputs in a canopy height model (CHM) further described below, which finally went

through an accuracy test (Santoso et al. 2013; Mweresa et al. 2017; Halin et al. 2017).

At stage 3, the canopy cover value was calculated using the data coming from both the CHM and from a "visual classification" method. The CHM value was used to define two classes of land: "enclosed land" (i.e., areas with tree cover: CHM > 5m), vs. "open land" (i.e., areas without tree cover: CHM < 5 m) (Padró et al. 2018). In the visual classification method, enclosed vs. open land was identified manually based on visible features on orthophotos.

Both datasets were then used to calculate the all return cover index (ARCI)¹⁴ using a formula adapted from Ma et al. (2017):

$$ARCI = \frac{\sum AllCanopy}{\sum AllTotal} \times 100\%$$

Note:

$\sum AllCanopy$ = Sums all pixel with trees cover ("enclosed land")

$\sum AllTotal$ = Sums all pixel ("enclosed land" + "open land")

10 Presented as the leading photogrammetry software for professional drone mapping. <https://www.pix4d.com/product/pix4dmapper-photogrammetry-software>

11 A digital elevation model (DEM) is a 3D digital graphic representation of the ground surface topography or terrain.

12 ArcMap is the main component of the ArcGIS suite of geospatial processing programs, developed by Esri. It is primarily used to create, view, edit and analyze geospatial data. See: <https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>

13 A raster refers to a rectangular grid of pixels. Each pixel's color can then be specified by a number of bits.

14 A method often used in Light Detection and Ranging (LiDAR)

The ARCI, which ranges between 0 and 1, reflects the proportion of enclosed land in the AOI and can be used as a proxy for canopy cover. The higher the ARCI, the denser the canopy cover. Results obtained from both methods were then analyzed and compared.

Data analysis

In remote sensing imagery, the ground sampling distance (GSD) is the distance between two adjacent pixels' centers as measured on the ground. The GSD reflects how sampling limits the spatial resolution of the resulting image. The higher the GSD, the lower the picture resolution and level of detail (Hernina et al. 2019). A GSD below 0.3 m is considered to produce high-quality images (Lillesand et al. 2015). According to Susetyo et al. (2017), UAV images can be categorized as high-resolution images because the resolution is two to four times higher than high-resolution satellite imagery. UAV images of various ACs and locations came with various average GSD and average density, as illustrated in **Table 1**. The average GSDs, obtained with a 12-megapixel camera with 2.5 mm zoom, ranged from 3.53 to 4.77 cm. These GSD values can be considered very low and are associated with very high-resolution pictures.

A point cloud is a set of data points, each associated with its spatial coordinates, representing a 3D shape or object. When point cloud data is processed into a 3D digital model, each point, with its coordinates, represents a pixel in the overall picture. A point cloud is used to create DTMs and contour lines at the end of the process in the Pix4D Mapper software (Sutanto and Ridwan 2016). Point cloud density refers to the number of coordinates collected per unit area. The higher the point cloud density, the higher the image resolution. The average point cloud density depends on canopy density level and on the slope of the location (Domingo et al. 2019). The shooting location for AC4 has a steeper slope compared to the other ACs. Therefore, the resulting point cloud density and the resulting quality of UAV images is lower for AC4.

Estimation of field time

Table 2 shows that the use of drones (model time) saves a lot of time when compared to inventories realized directly by field workers and hence could reduce drastically the costs of forest inventories (see also Priyo and Paridi 2018). According to Yovi (2019), because of the drudgery of field work and because of their direct interaction with sources of danger in forests, forest rangers and field workers

Table 1 The variations of UAV image resolution and point cloud density

No	Age class	Location height	Tree age average (in years)	Average GSD (cm)	Average density (m ³)
1	AC4	461 masl	16-20	4.77	23.67
2	AC6	133 masl	26-30	3.53	54.41
3	AC8	125 masl	36-40	4.21	30.55

Note: "masl" stand for "meter above sea level".

Table 2 The comparison of drone and field time

No	Age class	Number of photos taken	Drone time per 30 trees	Field-worker time per 30 trees
1	AC4	208	5hours 48minutes 21seconds	2 days
2	AC6	613	9hours 31minutes 17seconds	
3	AC8	551	8hours 41minutes 25seconds	

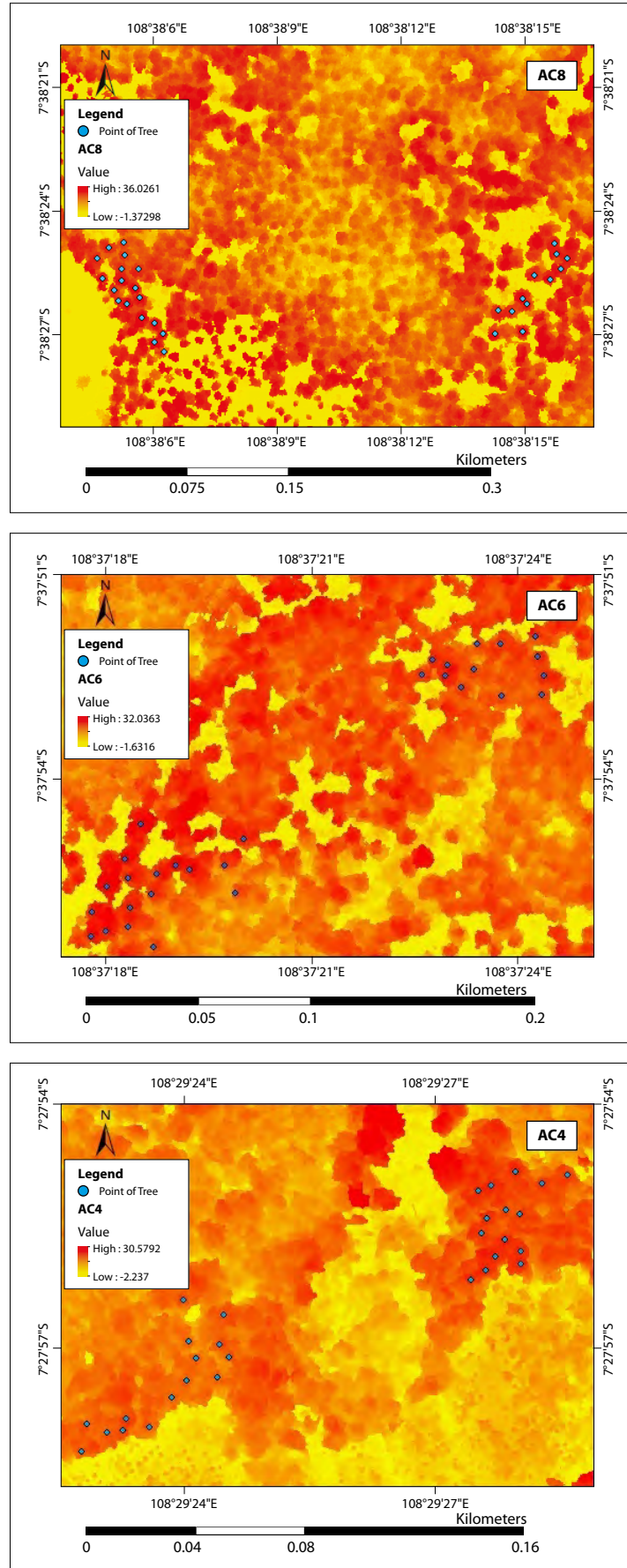


Figure 4. CHM Value

Source: Authors

Table 3. Tree height model derived from CHM

No	Age class	Intercept	Slope	R	R ²	%SE
1	AC4	2.5739	0.8435	0.937	0.877	8
2	AC6	0.5431	0.9691	0.967	0,936	5.9
3	AC8	0.5381	0.9554	0.950	0.903	8.3

Note: R2 denotes the coefficient of determination: R2 ranges between 0 and 1. The higher the R2, the stronger the correlation between the two variables. SE denotes the standard error.

are at risk of physical and mental exhaustion. Drones would help save time, reduce costs, and prevent potential hazards to field workers.

Results: Canopy height model (CHM)

Estimating tree height and tree diameter

The canopy height model (CHM) value, defined as the difference between DSM and DTM values in each pixel, is a proxy for tree height. The CHM value is shown in yellow to red in **Figure 4**, while the sampled tree coordinate position is shown in blue circles.

In **Figure 4**, red reflects higher CHM values, while yellow shows the opposite. The average CHM value found for AC4, AC6, and AC8 were 19.46 m, 20.03 m, and 27.77 m respectively. Like previous studies (Zhao et al. 2013; Wu et al. 2019), this study sometimes found negative CHM values due to biases or errors produced by the model, in particular where the point cloud density obtained from UAV images was too low.

A simple linear regression, illustrated in **Figure 5** and **Table 3**, shows a very strong correlation between tree height and the CHM value. The strongest correlation is observed for AC6. Then, **Figure 5** and **Table 4** illustrate the very strong correlation between tree DBH and the CHM value. The correlation observed has similarities for all of the ACs. In all ACs, the percentage SE value is very low.

Estimating canopy cover area

Canopy cover area can be very useful for assessing and monitoring: deforestation rate; wildlife habitat, especially for arboreal animals; and other ecosystem services. Canopy cover area can be used as a proxy to estimate the extent and quality of wildlife habitat for these arboreal animals, as well as the related feed potential. Deforestation rate control contributes to preserving the temperature stability of the Earth's surface. Tree canopies play a crucial part in giving protection from direct solar radiation and thermal comfort, thus contributing to the mitigation of climate change impacts (Wu et al. 2016). Therefore, the effective and efficient estimation of canopy cover area is essential in supporting forest conservation and climate change mitigation and adaptation efforts. High-quality UAV images can help monitor canopy cover and deforestation rate very precisely.

As mentioned above, this study compares the canopy cover information derived both from CHM values and from visual classification. Canopy cover area is estimated at 7803.5 m², 6053,5 m² and 1221 m² respectively in AC4, AC6, and AC8.

Figure 6 shows the variety of canopy covers, from low to high density, present in each AC. As a result, the ARCI varies significantly across ACs, from 0.625 to 0.895, as shown in **Table 5**. Visually, there is no significant difference in the canopy cover obtained through the CHM or by visual classification. **Table 5** (rightmost column) shows small numerical differences in the ARCI obtained by the two methods, demonstrating the relevance of the CHM to estimating canopy cover area.

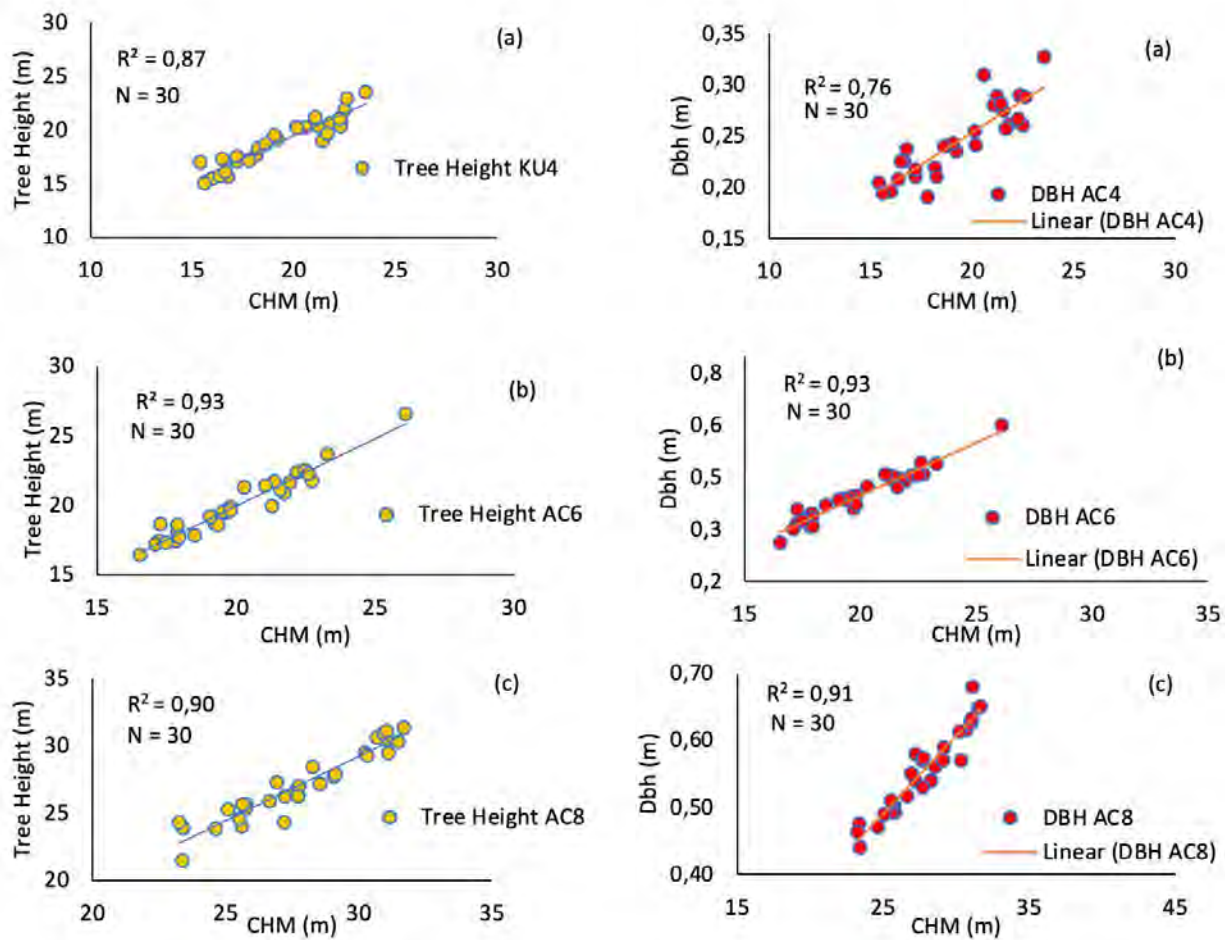


Figure 5. Linear relationships between CHM value, tree height and DBH

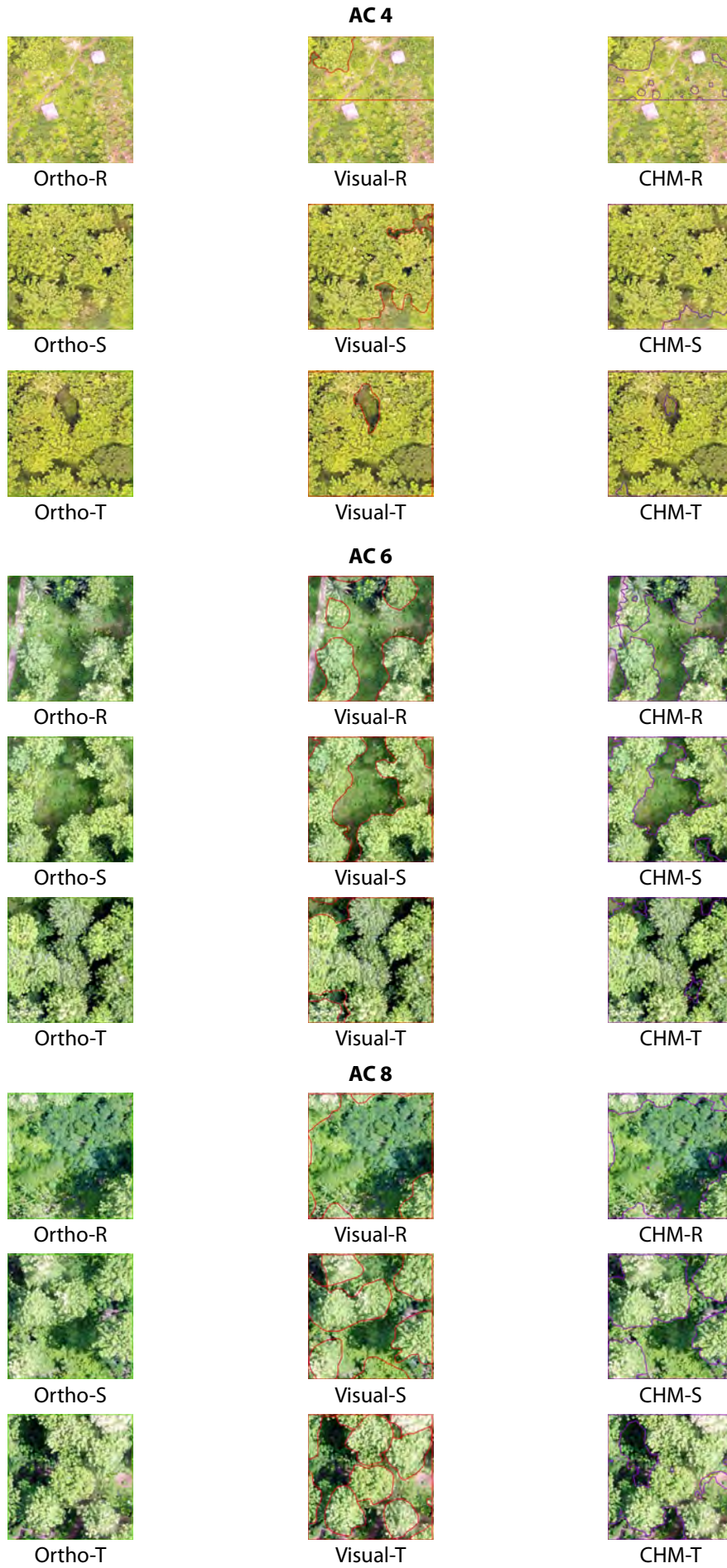
Source: Authors

Table 4 Tree diameter model derived from CHM

No	Age class	Intercept	Slope	R	R ²	%SE
1	AC4	0.0022	0.0126	0.870	0.757	1.8
2	AC6	-0.2116	0.0304	0.966	0.933	1.9
3	AC8	-0.0897	0.0232	0.956	0.913	1.8

Table 5. Canopy cover estimation

No	Age class	All return cover index (ARCI)		Difference between two methods
		Based on CHM value	Based on visual classification	
1	AC4	0.895	0.867	0.028
2	AC6	0.702	0.778	0.076
3	AC8	0.723	0.625	0.098



Information: R = low density, S = medium density, and T = high density

Figure 6. Sample crown area results of visual classification and CHM at AC4, AC6, and AC8

Source: Authors

Conclusion: the potential of drones for forest conservation

This study shows the high potential of drones for estimating tree height, tree diameter and canopy cover area. Drones can acquire high-quality pictures (high resolution and point cloud density) which, after processing, can lead to very precise estimates of these three parameters much more quickly and at a much lower cost than field forest inventories.

In turn, monitoring these parameters can support forest conservation, such as by helping to identify and monitor mangrove forest dynamics (Salim et al. 2018), estimate above-ground biomass (d'Oliveira et al. 2020) and carbon stocks in a forest area, or assess other ecosystem services. Tree height, tree diameter, and canopy cover area are critical parameters for the estimation of above-ground biomass. Above-ground biomass estimates can then be used to evaluate carbon stock. The use of drones can thus facilitate the monitoring of carbon stocks, offering potential options to facilitate uptake of carbon credit schemes.

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Development, testing and implementation of insect-catching drones

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Abstract

The decline of insect populations around the world has far-reaching ecological consequences and calls for improved insect monitoring systems. However, given the importance of flying insects as pollinators or feed for higher trophic levels, insect populations must be monitored at different heights. This pilot study aims to develop an innovative method that uses sweep net-carrying drones to easily observe the abundance and diversity of insect populations at different heights and times of day, following different flight schemes, at various sample sites, with limited or difficult access.

A total of 2,204 insects were caught via three different treatments (a malaise trap and two drone-net designs) at 17 sampling sites, covering four different types of habitats (hedge, grassland, rapeseed and wheat field) in the north-western Uckermark region of Germany. The number of insects caught decreased with altitude. Around 62 percent of the captured insects (1,370 insects) were caught with a malaise trap. Overall, drones equipped with fixed nets caught a larger number of insects than drones equipped with a single hanging net, with 616 and 218 individuals in total (including hedges) respectively. Among the habitats, hedges (885 insects) caught the largest number of insects, followed by rapeseed, wheat and grassland. Twice as many insects were caught during the afternoon and evening than in the morning. The drones captured 281 insects while flying with or against the wind, and 244 while flying perpendicular to the wind (excluding hedges monitored following a single flight scheme). The study showed that drones can offer an alternative to conventional sweep nets and suction traps if they become affordable for farmers, hunters, ecologists and entomologists.

Keywords: *Agroforestry, Ecology, Entomology, Drones, Insect decline*

Introduction and background

Drones have numerous applications in the field of species conservation and management, such as aerial censuses of large game, counting primate nests, scaring away and deterring birds in the agricultural and aviation industries, including as an easy-to-use alternative to traditional scarecrows and tamed birds of prey (Dronesville 2020; Perkins 2018), in a stealth anti-poaching approach (Burke et al. 2019). Drones are also used for pest control in urban settings to search for pest breeding points, reducing manual labour (Rajesh 2021; Richards 2021). Furthermore, they have proven very effective in agroforestry management approaches such as weed control, mapping seagrass, and the application of fertilizers and pesticides for precise spatial seeding of crops and trees (Hill 2018).

Insect populations are declining around the world (e.g. Hallmann et al. 2017; Leather 2017). This decline has far-reaching ecological consequences, particularly for pollination services and the trophic chain (Powney 2019; Jerrentrup et al. 2017). Many insect trapping possibilities already exist and are widely used (e.g. malaise traps, window traps and sweep nets), but almost all of them operate close to the ground. Insect traps that sample at different heights (e.g. malaise and window traps) are usually fixed in one place or difficult to move. A rapid comparison of ground traps shows that:

- Fixed ground traps, such as malaise and window traps, are susceptible to interference from wind and wet climatic conditions, as well as anthropogenic activities, such as damage from agricultural activities and large mammals (Department of Conservation 2016).
- Window and malaise traps face similar criticisms (Wheater et al. 2011): both collect large numbers of insects and are therefore considered lethal to non-targeted bycatches and protected species.
- Sweep netting is labour-intensive and limited to a range of twice the length of the operator's arm. The delicate net can be easily damaged if stuck in vegetation while sweeping.

- Handheld suction (vacuum-type) samplers can trap flying insects that prefer to stay close to the ground vegetation. However, they are labour-intensive, bulky and costly, may suffer from low suction speeds, and can damage ground vegetation (Wheater et al., 2011).
- Rothamsted suction (chimney-type) traps are fixed bulky structures (12.2 m above ground); they are set at a specific height to target a single species (aphids) (Bell et al. 2015).

Malaise traps are used in this study along with drones and are also criticized for their transportation and setup time. From field experience:

- Drones may experience calibration issues if transported roughly.
- There is no significant difference in setup time between the two methods.
- Malaise traps can be left alone, but drones require constant care and visual line of sight (VLOS).
- Neither method is adapted to rainy and moist conditions.

Considering the importance of flying insects, they must also be monitored at different heights. Using drones for entomological monitoring provides a larger degree of freedom to assess the abundance and diversity of insects at different heights. Insects can be sampled dynamically, not only vertically but also horizontally, over large areas. In other words, sampling places and times can be changed quickly, even in real time according to research needs. Innovative drone technologies have allowed entomologists and ecologists to study and monitor insects from varied spatial, trophic and pollination perspectives. However, the potential of drones for ecological (insect and other wildlife) monitoring is still largely untapped in many countries. So far, only two trial studies have been conducted on the use of drones to catch insects in the Asia-Pacific region: one in South Korea (Kim et al. 2018), and one in Australia (Christensen 2019; SWCCNRM 2019). Another study has been implemented in the USA (Neufeld et al. 2019).

This study compared three insect-catching methods: (i) two dynamic methods, using drones equipped with a hanging net or fixed net that can sample insects in different air layers and over large areas, and (ii) one static method (a malaise trap). The drones flew at heights of 1–33 m and the malaise trap was set up on the ground covering a height of up to 1 m. There were 17 sampling sites across the landscape matrix (comprising four grassland, five hedge, four rapeseed and four wheat sampling sites).

The main objectives of the study were to:

- compare the effectiveness of two different drones using different insect-trapping net designs;
- test flight efficiency with respect to wind directions;
- compare the number of insects caught between both drones and the malaise trap;
- determine the diversity of insects caught across sampling sites, by height and by time of day;
- identify the insects caught to their taxonomic order level (possibly species level);

- suggest recommendations to improve the implementation of insect-catching methods.

Research design and methods

The implementation plan was divided into three main modules, further decomposed into varied packages and tasks, as illustrated in **Figure 1**. Outdoor activities took place from May until July 2020, whereas indoor activities occurred from August until October 2020.

Module 1. Technological development

Three different insect-catching methods – (i) a Mavic Pro drone with a hanging net, (ii) a Phantom 2 drone with two fixed nets, and (iii) a malaise trap – were tested on all sampling sites, sampling insects at predefined heights above ground and at different times of the day. Drones were used to catch insects dynamically (i.e. in motion), whereas malaise traps caught insects statically. Comparisons of insect abundance and diversity was done between all three methods.

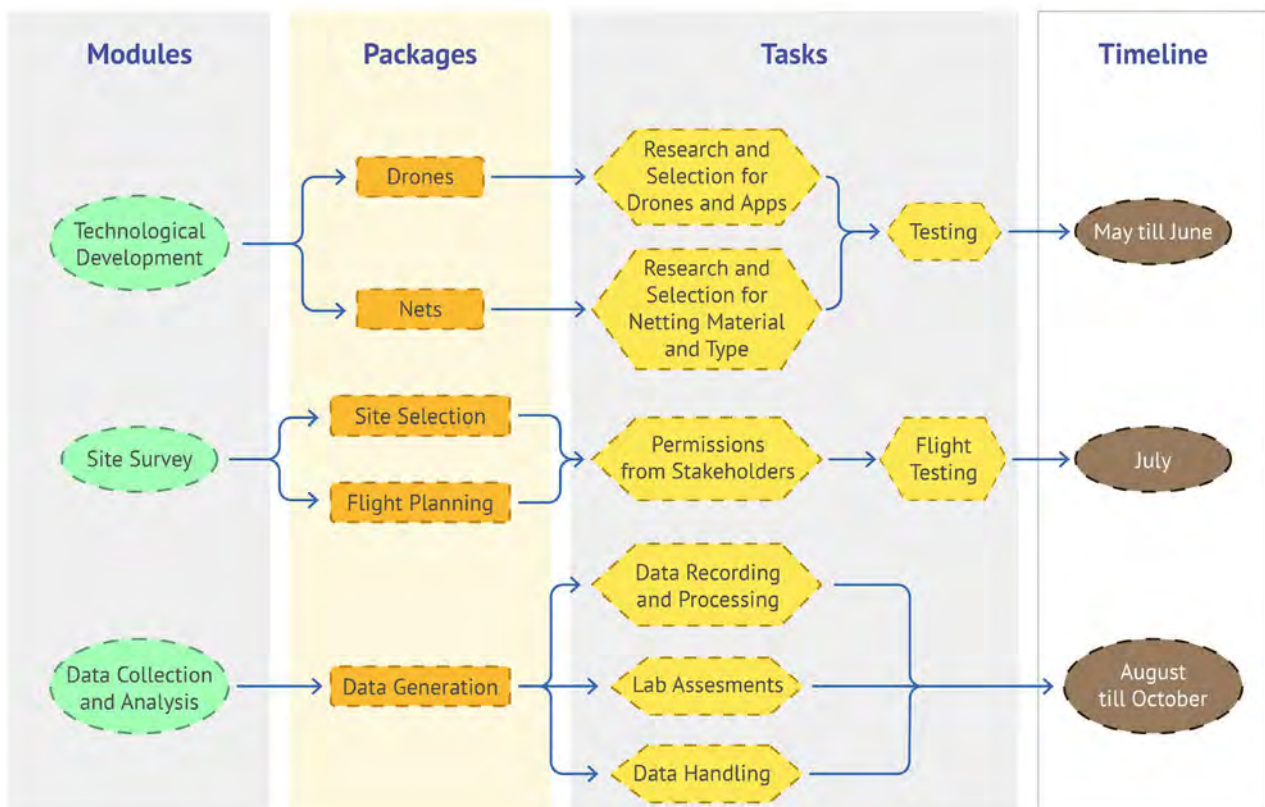


Figure 1. Testing and implementation plan of the conducted study.

Source: Authors



Figure 2. Hanging net specifications (left) – Mavic Pro with cane and fishing line (3 m) attached to net (right) © Shahrukh Kamran

Mavic Pro with hanging net

The first drone, a Mavic Pro,¹ was equipped with a single hanging net, hung with a long plastic thread (fishing line) from the drone like a fishing creel (**Figure 2**). The net was designed with double (external and internal) layers so that the insects could not escape after being trapped. To extract the insects out of the net, a specially designed cotton cap was attached with Velcro at the end of the trap. The overall length of the outer net layer was 80 cm, with a 40 cm inner net layer (**Figure 2 left**). The diameter of the net was about 38 cm (**Figure 2**). The net was approximately twice the size of a fixed-net design. It was attached with an almost 3 m fishing line² to avoid direct downward thrust from propellers. At heights of above 20 m, net orientation was an issue due to an increase in wind gusts, and inertia caused the drones to lose calibration, control and battery power.

Phantom 2 with two fixed nets

The second drone, a Phantom 2,³ had two nets fixed on both sides of a 1 m rod attached to the drone's special landing legs (**Figure 3**). The nets were fixed at far ends of the rod

to avoid the thrust from the propeller.⁴ The rod length was adjusted to best maintain the drones' centre of gravity but still faced some technical issues (i.e. instability in flight and a loss of hovering ability), which may have been caused by attaching the metal rod in close proximity to the drone sensors. An unsuccessful attempt was made to solve this technical issue by using a cane stick to avoid disturbance caused by the metal. Extending the legs with stilt-like cane sticks caused the drone to crash-land due to interference with its aerodynamic design. This issue was beyond the team's expertise and remained unresolved.

The net frame consisted of easily obtainable knitting frames with a diameter of 25 cm. This drone was much more susceptible to loss of control than the Mavic Pro, such as during sudden changes in wind direction. Due to this instability issue, the Phantom 2 was kept in constant movement to avoid crashing. For reasons unknown, steady flight was possible only by controlling the drone manually, which made it difficult to maintain the correct height. A slender platform was arranged for the launch but required assisted hand-forced landings. However, on a few occasions, control of the drone was lost due to wind drag and it crashed.

1 Mavic Pro is a series of UAV developed by DJI, a Chinese technology company.

2 Hence the drone must fly at 7 m to catch insects at a height of 4 m.

3 Phantom is a series of UAV also developed by DJI.

4 i.e. the wind force created by the drone's rotors.

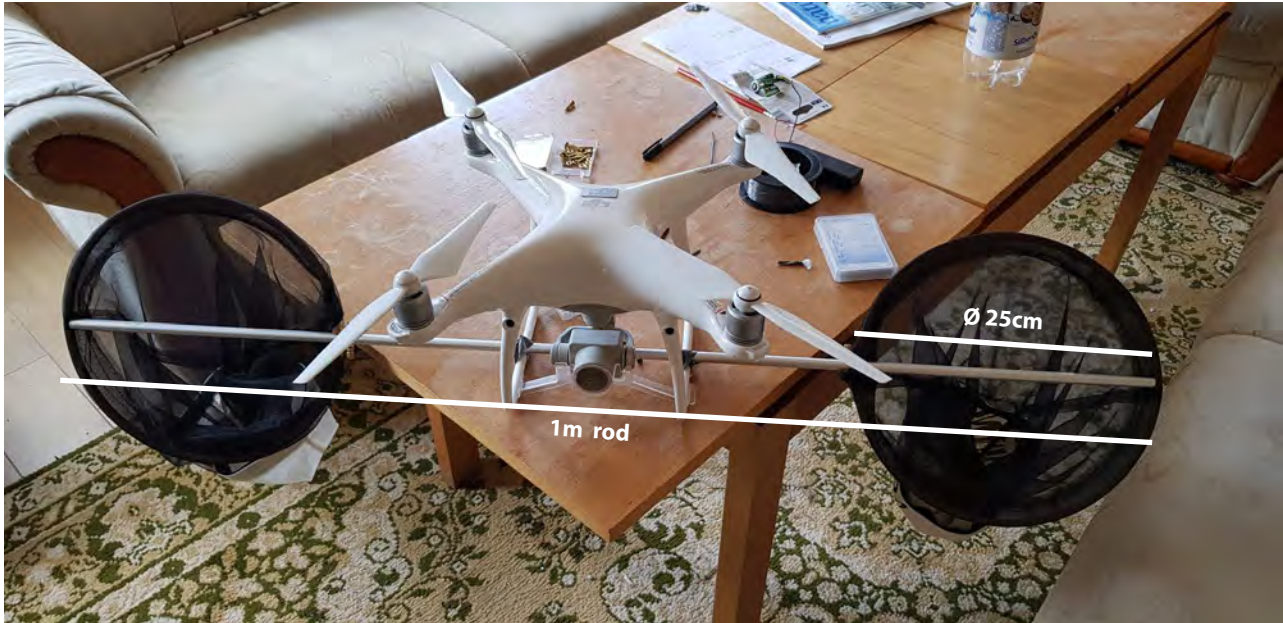


Figure 3. Fixed net – Phantom 2 © Shahrukh Kamran



Figure 4. Malaise trap (fine baffles supported vertically by canes, rod and guy ropes) for fast flying insects © Shahrukh Kamran

Processing apps and websites

The DJI GO 4 drone application was used for drone calibration, and Litchi (paid version) was used for flight path processing and manual control. The Airdata UAV (paid version) online platform was used for the processing of flight logs. UAV Forecast was used to determine flight conditions. DroneDeploy (trial version) was used for image processing. The AgrarWetter website was used for weather forecasts.

Malaise trap

The malaise trap was put in place to sample insect populations up to 1 m in height and always placed perpendicular to the wind (**Figure 4**). A fine netted vertical structure intercepts insects in flight. As they hit the centre partition, the sloping tent-like roof guides them to crawl upwards into a collecting jar fixed at the highest point, which contains a small quantity of alcohol (Wheater and Cook 2016). These traps face some

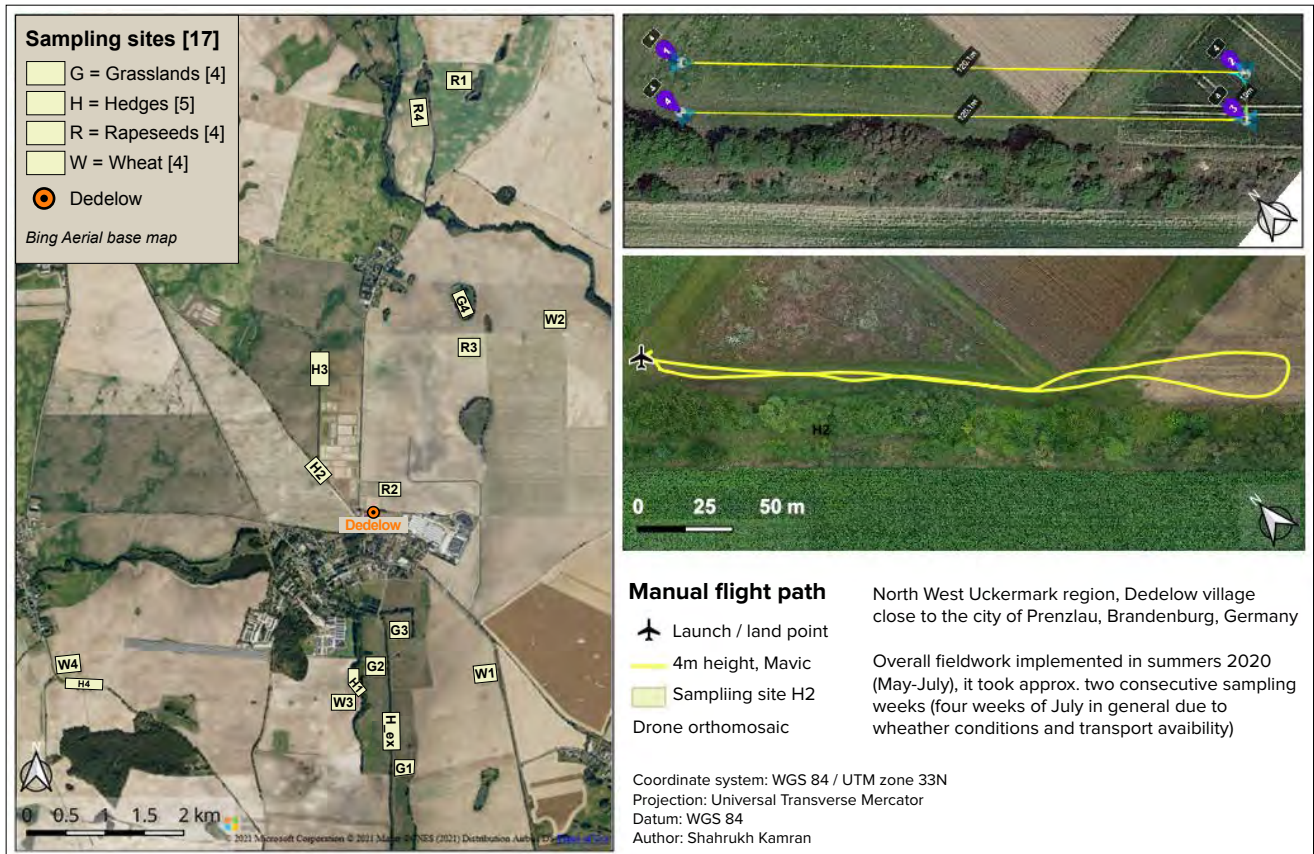


Figure 5. Sampling sites around Dedelow (left); the planned flight path in 'Litchi - Mission Hub', covering 250 m U-transect, both lengths 120 m each with 10 m curve (top right); actual manual flight path, real-time drone image at base (bottom right)

Source: Authors

limitations: they may attract vandals, and they cannot be used in wet and windy conditions. It is strongly recommended that these traps be supplemented with additional trapping methods such as drone sweep-netting methods (Wheater et al. 2011).

Module 2. Site survey

This study took place in Dedelow, close to the town of Prenzlau, Brandenburg, in the northwestern Uckermark region of Germany. The study area is an open agricultural landscape (**Figure 5 left**). Four different habitat types were sampled (hedges, grasslands, rapeseed and wheat fields). Each habitat type was sampled four times in different areas (no repetition of the same sampling site). Hedges were sampled five

times.⁵ Drone regulations (Juniper 2016) were taken into account by applying a 150 m safety buffer around residential colonies, buildings and transmission lines, and a 100 m buffer around roads and dairy plants. In addition, permissions to access sites were obtained from the landowners, farmers and hunters.

Flight planning

A U-shaped transect was designed with a single point for launching and landing (**Figure 5**). The planned length of the U-transect was 125 m (sampled at both sides, with a 10 m curve). However, drone flights were controlled

5 The project was carried out at 17 sampling sites in total (Figure 5 left). An additional hedge sampling site (H-ex or H_5) was selected to be on the safe side in case permission to other selected sites was denied.

manually for various technical reasons,⁶ and in real conditions, many factors can affect altitude and transect length.⁷ As a result, the real U-transect length varied across flights (up to +56 m). In general, both drones faced problems at heights above 20 m, such as mid-flight inertia and calibration issues.⁸ Maintaining stable height was much more difficult with the Phantom 2 because of its aforementioned stability issues.

The winds experienced during the field activity phase were usually very strong (often 23–36 km h⁻¹, compared to a recommended wind speed of 14–20 km h⁻¹). Drones are capable of measuring average wind speed, direction and maximum gust during each flight.⁹ Some flights were cancelled because of unsuitable wind conditions (average speed above 22 km h⁻¹ and maximum gust speed of over 28 km h⁻¹). Two proposed flight schemes were implemented (with or against the wind, versus perpendicular to the wind) to determine which scheme was the most effective at catching insects and to test the assumption that insects prefer to take flight perpendicularly to the wind. However, only one flight scheme was applicable to the hedges, i.e. following the hedge.¹⁰ Similarly, for one grassland, only one flight scheme

was tested because of the small size of the sampling site.

To cover the large number of flights per site, at least three batteries per drone were necessary based on wind conditions, site accessibility and charging of battery units. To cover more sites in a day, it is recommended to carry extra sets of batteries, along with double charging units that can be connected with the vehicle's battery system.

Module 3. Data collection and analysis

Data collected by the drones were partially recorded as a hardcopy, then partially recorded and processed using software, and finally recoded into Excel sheets. Data were later processed and organized for data handling in the R programming language. The initial data representation and descriptive analysis are being presented in this paper.

Different methods were used to extract insects from the nets. Insects caught with the malaise trap were collected from the alcohol-filled containers attached. A battery-powered aspirator with specially-designed containers was also used to collect the live insects from the trap mesh (**Figure 6 left**). A cold spray (liquid refrigerant) was used to freeze the trapped flying insects so that they could be easily collected (**Figure 6 right**).

Insects caught with the open drone nets were sprayed immediately after landing,¹¹ collected at the bottom of the net into the attached white cotton cloth, then counted, recorded and preserved with a solution of ethanol (96 percent). The specimens were then identified using a digital microscope in an ecological lab (**Figure 7**) up to their taxonomic order.¹²

6 e.g., to avoid inertia, sudden wind gusts and more drag on nets at higher altitudes; to control hanging net orientation; to address mid-flight drone calibration issues (for both drones). Moreover, the centre of gravity issue caused by attaching the net structure very close to the body of the Phantom 2 led to a series of other aerodynamic problems with hovering and launching/landing.

7 Such as topography, wind conditions, branches and other obstacles, manual control, and hanging net orientation.

8 Specifically related to the hanging net – Mavic Pro design, the drone was dragged by the hanging net due to sudden wind gusts. When attempting to regain control, the drone became highly unstable and showed a recalibration warning upon landing.

9 All of these variables can be extracted from flight logs. Wind is calculated using the angle of the aircraft and the speed of the aircraft at each point of the flight. Wind values may not be recorded in the logs during sharp manoeuvres, such as steep decline or fast turns. See: <https://airdata.com/>.

10 Because at lower altitudes, vegetation and trees were a major obstacle for flying perpendicular to the hedge.

11 However, a few specimens still managed to escape.

12 As we are currently lacking the expertise needed to identify aerial insects up to their species level, we plan to order a DNA analysis of selected samples for species-level identification at a later stage.



Figure 6. Use of battery-powered aspirator (left); later cold spraying (right) © Shahrugh Kamran

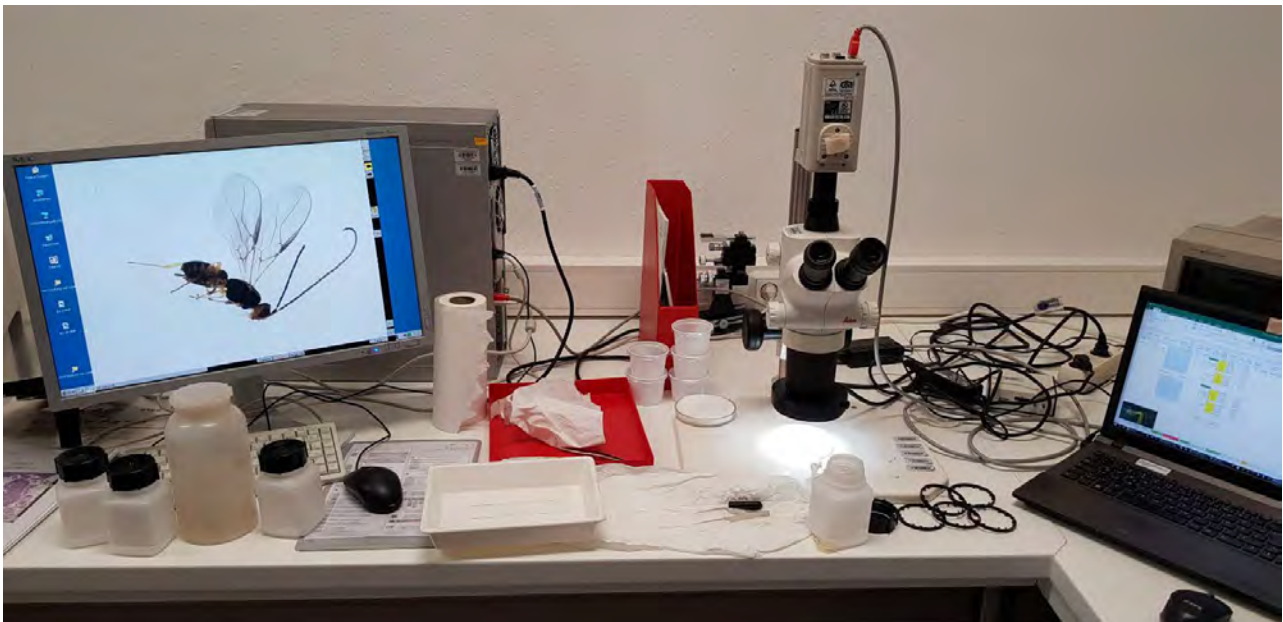


Figure 7. Insect identification in ecological lab © Shahrugh Kamran

Results

A total of 2,204 insects were caught in this pilot study. This section presents the first initial results of this study, still under the process of further evaluation, analysis and improvements.

Altitude, catching method and flight schemes

In total, both across all sites (hedges included), and in most sites, the largest

number of insects were caught at a height of 1 m with a malaise trap. This occurred despite the fact that the trap is static, because insect diversity and abundance are highest close to ground vegetation and because the malaise trap has the largest catching surface. Across all sites, 1,370 insects (62 percent of the total) were caught with malaise traps. The number of insects caught with drones decreases gradually with altitude, showing that only a few specialized insects fly at higher altitudes (**Figure 8**).

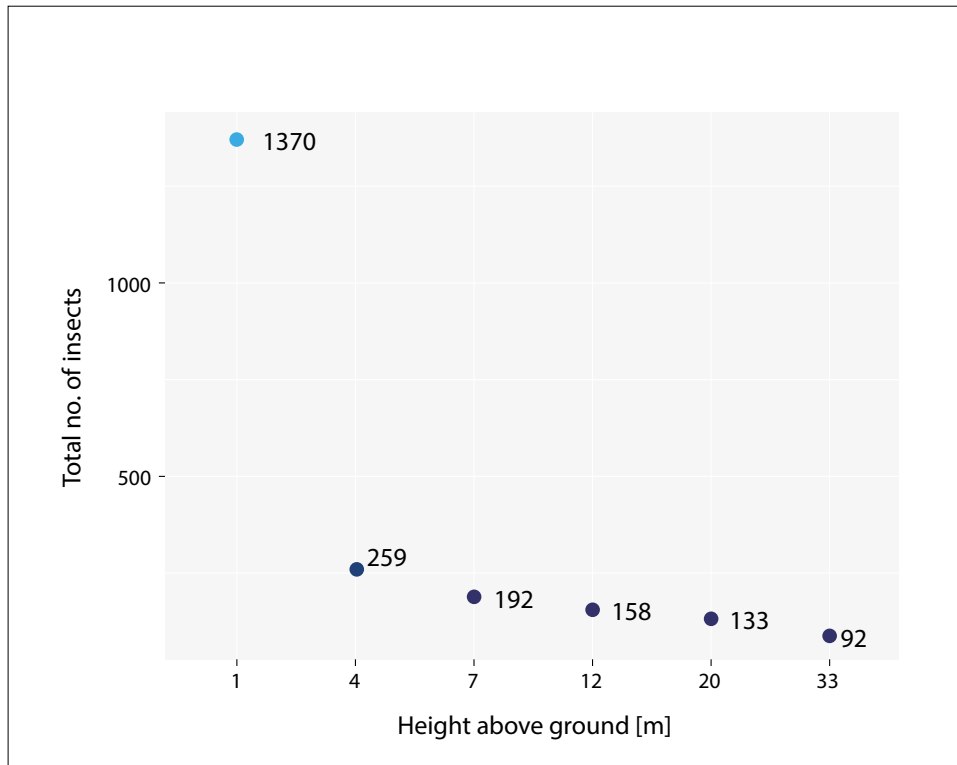


Figure 8. Number of insects caught at ground level (1m with malaise trap) and at five altitudes (with two drones)

Source: Authors

As only one flight scheme was implemented along the hedges, they are not directly comparable with the other habitats where two flight schemes were implemented and their results were thus processed separately. Overall, the Phantom 2, with its two fixed nets, caught more insects than the Mavic Pro, with its single hanging net, with 616 and 218 insects caught in total respectively including hedges, and 396 and 129 insects caught respectively when excluding hedges (see **Figures 9** and **10** for detailed results).

Across all habitats, excluding hedges monitored following a single flight scheme, 794 insects were caught with a malaise trap always placed perpendicular to the wind, 281 insects with drones flying with or against the wind, and 244 with drones flying perpendicular to the wind (**Figure 11**).

Habitat

Hedges accounted for the largest number (885) of insects caught among all habitats, despite the fact that hedges were all surveyed following a single flight scheme

(i.e. along the hedge), followed by rapeseed (623 individuals), wheat (484 individuals) and grasslands (212 individuals) (**Figure 12**).

Taxonomic order

Across all sites, 2,204 individuals were caught in total, including 2,129 flying and 75 non-flying individuals of nine different taxonomic orders (seven insects and two non-insect orders) (**Figure 13**). Besides flying insects, the bycatches included classes like Entognatha, which includes springtails (58 individuals), and arachnids (16 individuals), comprising 11 spiders and 5 ticks. Although they are not flying insects, they contribute to site biodiversity. Interestingly, ticks were caught clinging onto other flying specimens observed during lab identifications. Springtails are good jumpers and may have been caught during take-off or landing or accidentally sucked in by the aspirator. Similarly, spiders may have been caught either during their ballooning or during drone take-off and landing.

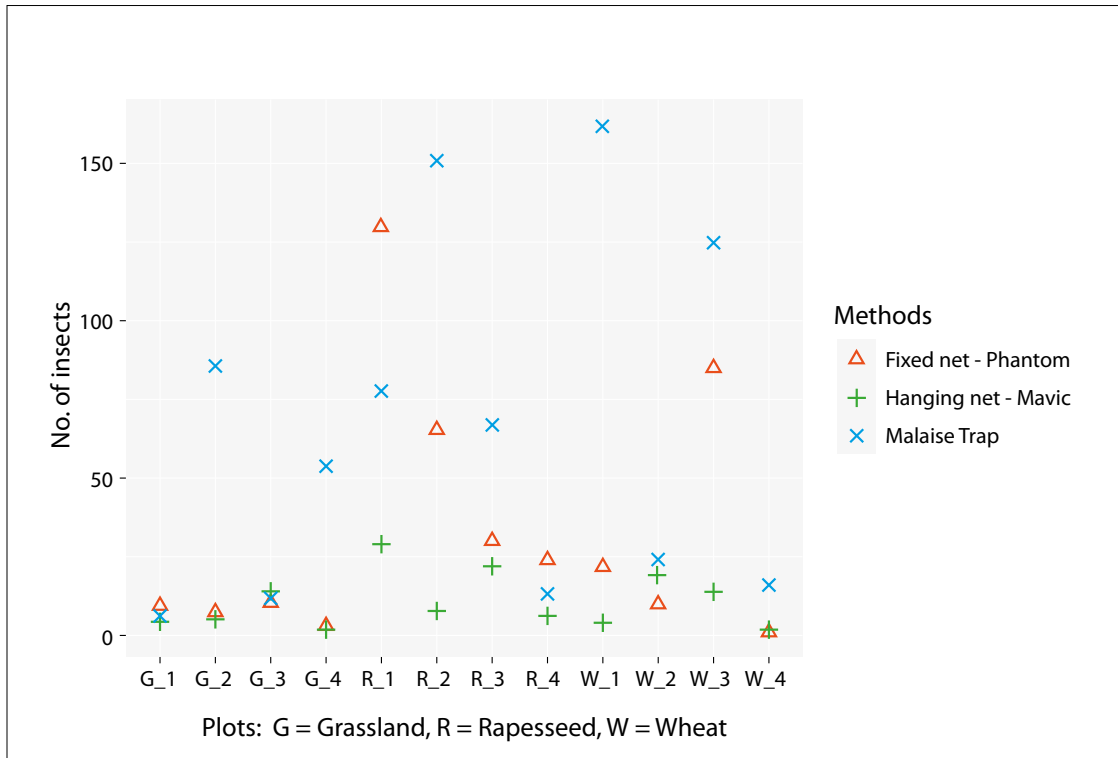


Figure 9. Number of insects caught with the three methods across habitats (excluding hedges)

Source: Authors

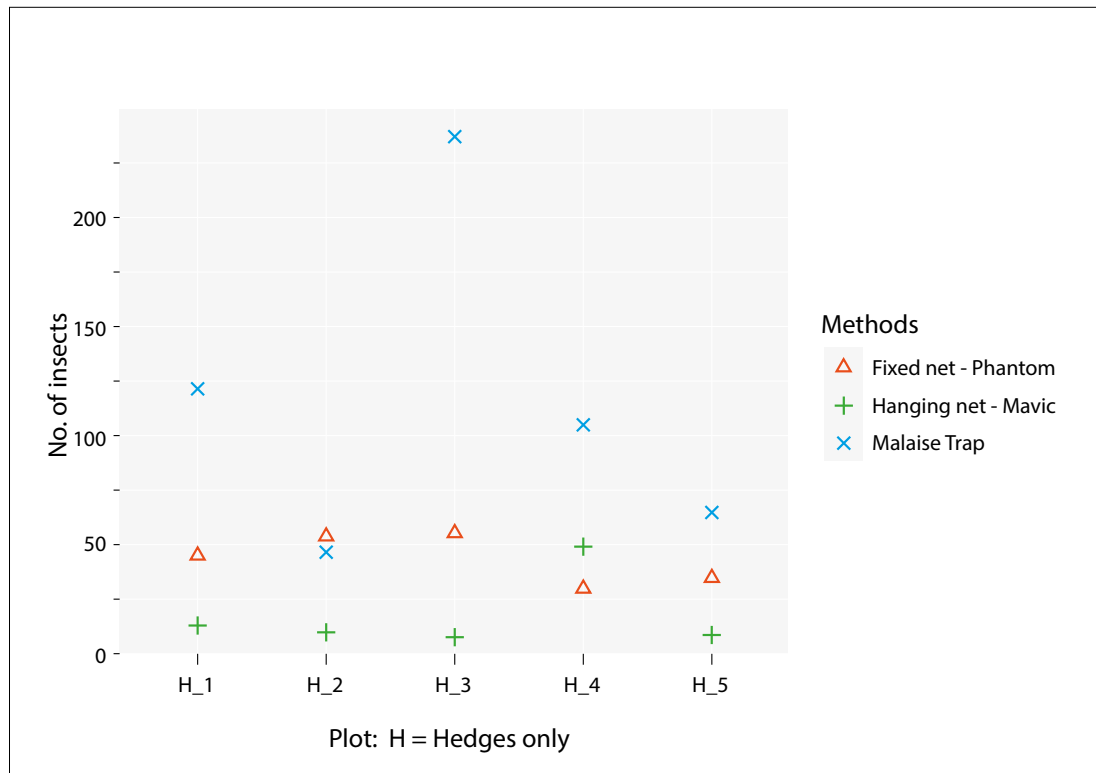


Figure 10. Number of insects caught with the three methods along hedges, using a single flight scheme

Source: Authors

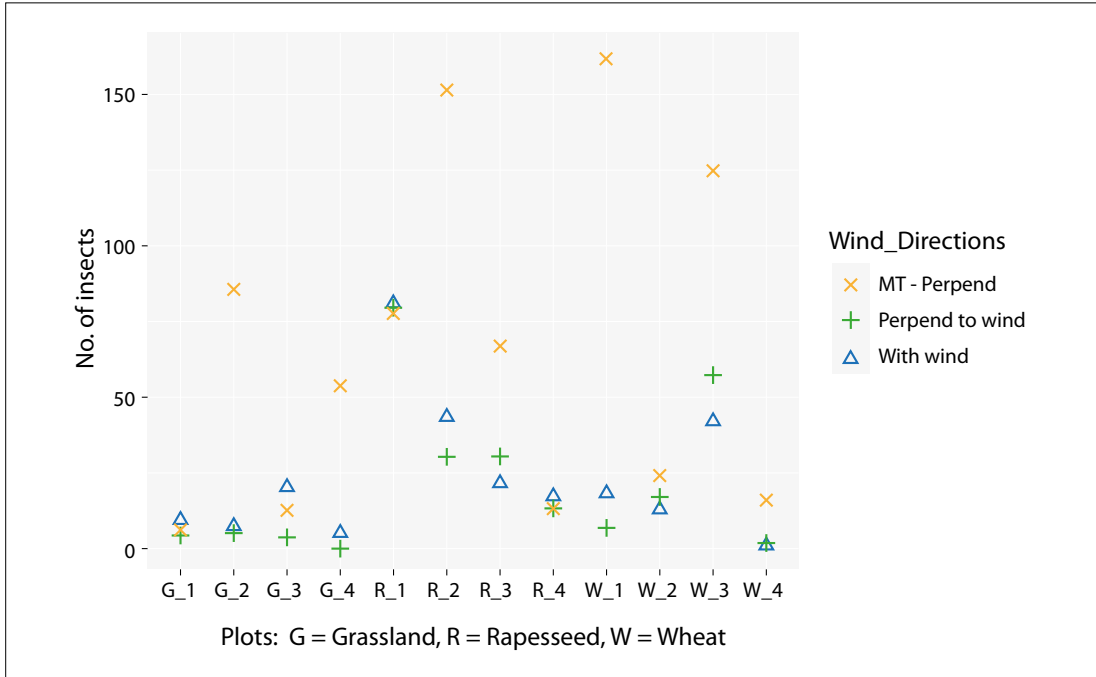


Figure 11. Number of insects caught, across habitats (excluding hedges) by flight scheme (w.r.t. wind directions)

Source: Authors

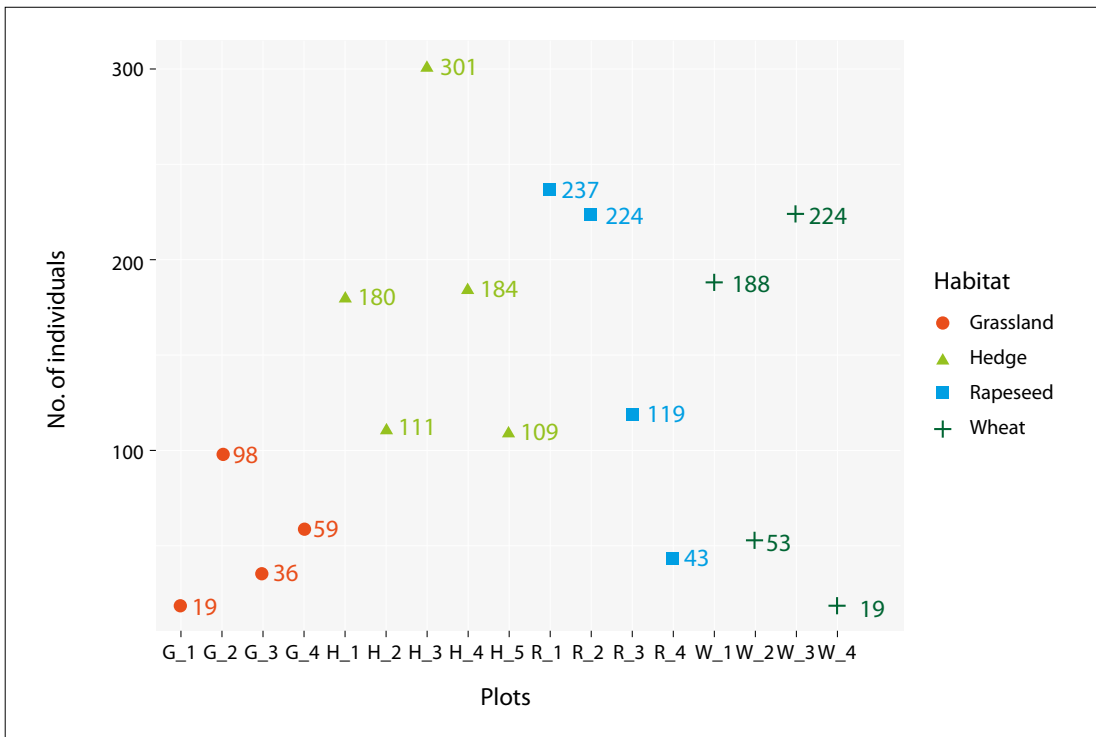


Figure 12. Number of insects caught by all three methods in diverse habitats

Note: the numbers for grassland, rapeseed and wheat have double as many transect line than those for hedges.

Source: Authors

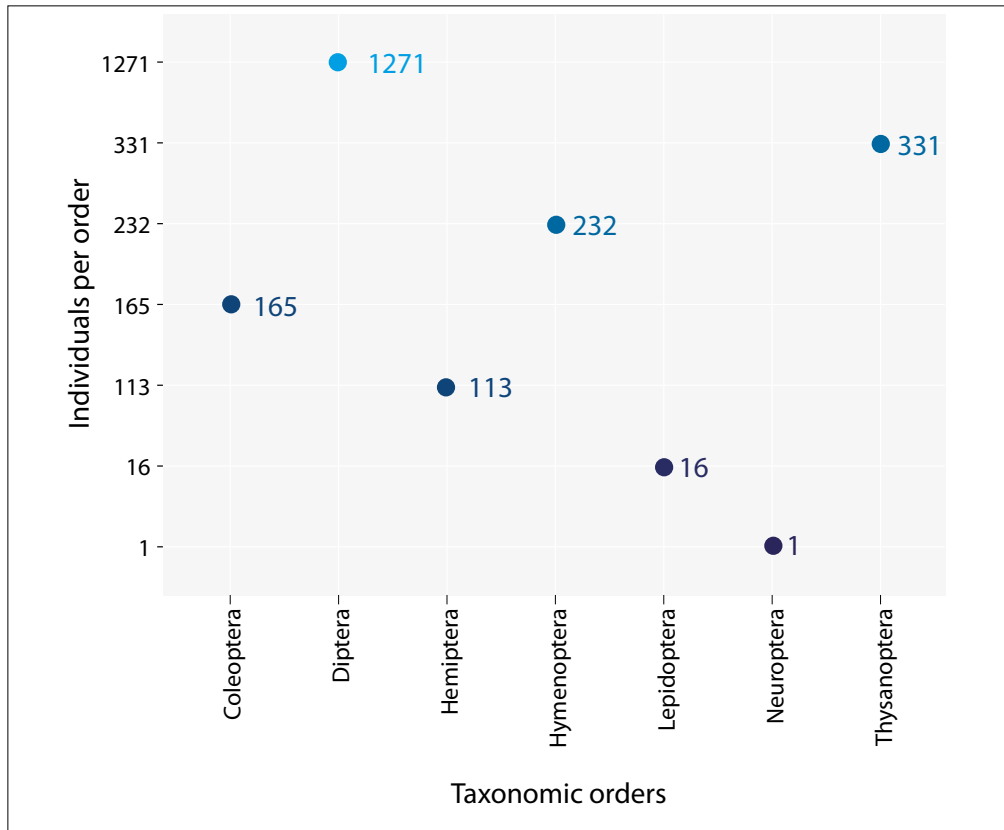


Figure 13. Flying insects only, by taxonomic orders (including hedges)

Source: Authors

Now focusing on flying insects, across all sampling sites, Dipterans were the most frequently caught, followed by Thysanopterans and Hymenopterans (**Figure 13**). Conversely, the fourth most frequently encountered order proved to be habitat-specific, e.g. Entognatha in grasslands, Hemipterans in hedges, and Coleopterans¹³ in both crop fields. Among the least encountered orders were Lepidopterans,¹⁴ Neuropterans (one individual) and one unknown.

Hedges were the most diverse sites, offering moist shady niches and less wind resistance on the levee side. Hedges with varied vertical and horizontal vegetation structures provide protection and foraging niches for a large community of insects.

The three catching methods do not show significant differences in terms of the variety of insects caught: flying insects caught with the malaise trap covered seven taxonomic orders, while insects caught with each type of drone (with fixed and hanging nets) covered five taxonomic orders.

Time of day and temperature

The appropriate time of day for flying drones was in the early morning due to calmer wind conditions. However, while suitable for drones, such conditions may not favour insect activity due to lower temperatures. All of the grassland sites were covered in the early morning due to constraints on site accessibility, such as grant preferences, transportation options, and distance from the field research centre. Grasslands were approached with all equipment stored in backpacks and an attached carrier with a

¹³ Including the family of the rove beetles (Staphylinidae).

¹⁴ Butterflies and moths (Lepidopterans) were only found in malaise traps, showing that they are not found at higher altitudes.

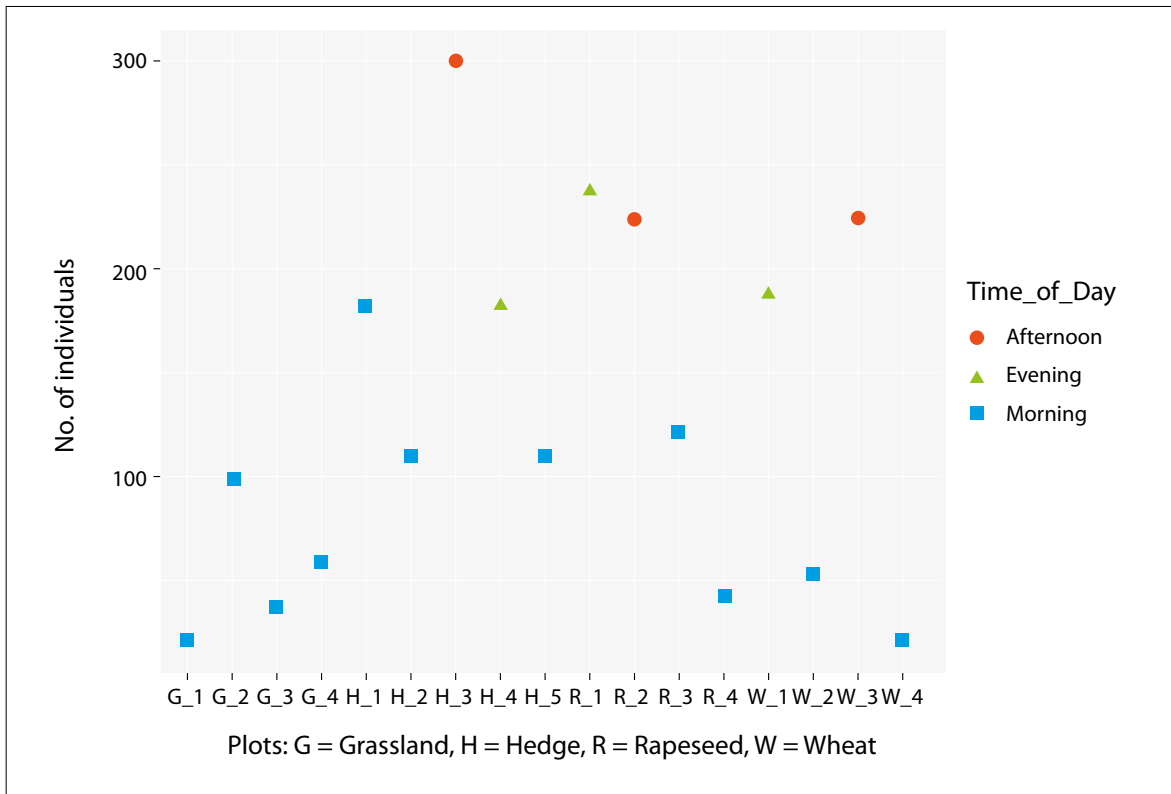


Figure 14. Number of insects caught per time of day across all sites.

Source: Authors

bicycle.¹⁵ The sampling time in grasslands and hedges sites was shorter than at other sites due to less insect activity in the morning, which resulted in less time spent on counting, and calmer wind conditions, allowing flights to be carried out smoothly.¹⁶

The initial results (without statistical analysis), illustrated in **Figure 14**, indicate that regardless of the habitat, the number of caught insects was consistently lower in the morning than in the afternoon and evening when temperatures are higher and lower respectively. This shows that entomological activity increases with temperature. Overall, the number of insects caught in grasslands (212 individuals) and the number of taxonomic

orders observed were the lowest because all grassland sites were sampled in the morning. Fewer insects were caught at two rapeseed and two wheat sites that were sampled in the morning than at the other sites for these crops, which were sampled in the afternoon and evening.

For hedges, three sites were sampled in the morning, one in the evening and one in the afternoon. At individual sampling sites, the highest activity was observed during the afternoon (301 insects caught in H_3 site) due to considerably high temperatures, followed by the evening (184 in H_4) and the morning (184 in H_1) (**Figure 14**). A similar number of individuals were caught at the H_1 and H_4 sites, probably because both sites experienced similar temperature ranges.

15 Drones may face calibration issues if handled roughly, such as when taken on bumpy bicycle rides. Recalibration in the field can sometimes be problematic due to poor internet reception at remote sites.

16 Normally, two sites were sampled per day. However, it was possible to sample three sites consecutively in the morning for grasslands and hedges.

Discussion

Social constraints

The stakeholders involved in this pilot study were landowners (local farmers and hunters), two regional universities (HNEE and PU)¹⁷ and two regional public research institutions (ZALF and IZW)¹⁸ focusing on agricultural landscapes, ecology and entomology. All landowners involved granted access to the sample sites. Some were even interested in the technological concept being applied. However, stakeholders were generally slightly hesitant due to concerns about crop damage and wildlife disturbance during field activities.

This pilot study, as well as former studies (Kim et al. 2018; Neufeld et al. 2019), shows the potential of integrating drones into ecology and entomology disciplines. Purchasing a drone is a one-time investment that provides the opportunity to execute one's own research by cooperating and volunteering with other local and regional stakeholders (e.g. private landowners, non-governmental organizations and research institutions). International and regional research institutions¹⁹ and universities can train and implement similar projects throughout Asia and the Pacific, such as with agricultural crops like rice, sugarcane, cotton, or with forest ecosystems. There is a need to facilitate such partnerships in developing countries through financial support, knowledge exchange and appropriate training. Such training should be easily understood by people from non-technical backgrounds. Only then can innovative technologies empower smallholders and local actors effectively, allowing them to contribute actively to ecological monitoring and management (e.g. ecological pest control).

17 HNEE – Eberswalde University for Sustainable Development; PU – Potsdam University

18 ZALF - Leibniz Centre for Agricultural Landscape and Land Use Research; IZW – Leibniz Institute for Zoo and Wildlife Research

19 Such as the Center for International Forestry Research (CIFOR), the World Agroforestry Centre (ICRAF), or the International Centre for Integrated Mountain Development (ICIMOD)

Legal constraints

In many parts of the world, existing UAV technologies cannot reach their full potential due to the lack of an appropriate legal framework (licensing permits, flight over private lands, weak regulations, etc.) (Jones 2017). Drone privacy laws and legislation approaches are typically divided into seven categories:²⁰ effective ban,²¹ outright ban,²² experimental VLOS,²³ VLOS required,²⁴ restrictions apply,²⁵ unrestricted, or no legislation. UAV technology is rapidly integrated in many disciplines and activities. This results in unstandardized regulations based on various drone uses and diverse perceptions of drones by national authorities, and overlaps among legislation approaches across countries. The aforementioned legislative approaches usually have one or more motives behind them, such as precautionary motives against appropriate legislation, ecological measures and homeland security measures.

Many Asian countries have no or weak UAV regulations (e.g. Pakistan, North Korea, Kazakhstan, Mongolia).²⁶ Countries with drone bans in Asia include Bhutan, Brunei Darussalam, Uzbekistan and the Maldives.

20 For more information on country-specific drone legislation and privacy laws, useful maps and databases, see for instance: <https://www.visualcapitalist.com/mapped-drone-privacy-laws-around-the-world/>; or <https://www.google.com/maps/d/u/0/embed?mid=1OkEtyCaGNjKhLeMr6L2IU975SP8&ll=-6.242789284104972%2C-69.08946399999996&z=2>

21 Regime whereby the country has a formal process for commercial drone licensing, but either requirements are impossible to meet, or licenses do not appear to have been approved (Jones 2017).

22 Regime whereby the country does not allow drones at all for commercial use (Jones 2017).

23 Experimental VLOS is a regime whereby pilots can fly a drone outside their field of vision, e.g. during a race.

24 Pilots must be able to see the drones at all times and must usually obtain a license or permit.

25 Drones must be registered, and/or additional observers are required.

26 See: <https://www.visualcapitalist.com/mapped-drone-privacy-laws-around-the-world/>

²⁷ Some countries allow hobby drones. However, when a drone is being shipped to the country, it may not be released from customs if no proof of transparent regulations exists.²⁸ Academic and research institutions could help in this situation by providing consultancy services to officials and by helping to develop transparent legislations adapted to various UAV models and various activities in various sectors (e.g. ecology, forestry and agriculture). Upscaling the adoption and use of UAV technologies will require capacity-building efforts and an evolution of mentalities. Drone pilot schools and drone governing committees can play a crucial role in developing a positive technological attitude.

Conclusion: key findings and recommendations

This pilot study was conducted in combination with another study on the coexistence of different aerial insectivores (swallows, bats) threatened by the decline in insect prey availability. It paved the way for improved sampling of insects at different heights to deepen knowledge on trophic interactions, such as foraging ecology and predator-prey relations among aerial insectivores. Drones have already been used for entomologically-related monitoring in a few case studies, such as monitoring for mosquitos (Richards 2021) and locusts (Rajesh 2021). These studies were not meant to sample or catch them but to focus on their habitat and feeding grounds respectively. In future, I believe that ecological researchers could get benefit from improvised drone-net designs that will be able to catch locust swarms. Catching destructive swarms will help with pest control and securing crops in many Asian and African countries. Hence, it could improve food and economic security in such regions, moreover caught locusts (as superfood) could possibly end up in local bushmeat markets and street food. Moreover, drones could also benefit pollinator studies, both by catching pollinators

and also by simultaneously documenting the flowering patterns taken by the drone's imagery sensors. This drone insect monitoring approach is not only limited to crops and open areas; similar methods can be applied on tree canopies.

This pilot study has led to further recommendations for future applications of insect-catching drones. Earlier studies (e.g. Kim et al. 2018) showed how remotely controlling the net direction on commercial drones can help avoid catching unwanted insects. Similar ideas can be applied to hobby drones. It was beyond the team's expertise to remotely control the direction of the nets during flight.

Besides the choice of net cover, choosing appropriate flight applications is another important task. Flight applications and data processing options can be selected from online hubs that provide various options depending on the site specifications and customization of drone use for different research projects. The choice of automated or manual flight controls depends on the user, the study objective and the technicalities to be faced. Sudden changes in wind speed and direction are difficult to control and may cause issues such as mid-flight calibration, sudden drag, inertia and missing recorded flight log parameters.²⁹ To avoid such wind issues, it is equally important to look for ideal times with calm wind conditions, but these times may not provide ideal temperatures for insect activity. These issues cannot be entirely solved within the scope of general-purpose hobby drones. Hobby or commercial drones specifically designed for such tasks will likely increase work efficiency.

The functionality of the nets is another important consideration. It is recommended to use white lightweight netting material to allow insects to be easily extracted. Another critical issue was the loss of hovering ability of the Phantom 2 drone when a foreign object was attached close to the drone's body. This issue

²⁷ See: <https://www.drone-made.com/post/asian-countries-with-drone-ban>

²⁸ See <https://uavcoach.com/drone-laws-in-pakistan/>

²⁹ Flight log parameters will not be recorded during sudden sharp manoeuvres, such as steep decline or fast turns. See: <https://airdata.com> Click or tap here to enter text.

could be solved by using drones with special designs to fix the nets to the drone. Such a drone could be an expensive customized drone or a hobby drone with an unusual design.

Furthermore, to choose a suitable sample site, it is recommended to look for appropriate wind conditions and surroundings, as not all sites will provide ideal conditions. Another factor to be taken into account is that the drones must be operated within the line of sight of the operator, which often limits their range. Conversely, surplus batteries and charging units can be used to increase the drone range and overall working efficiency. In theory, it is preferable to use a single line transect with launching and landing points at each end to fly from one point to another, which reduces labour, flight time and battery use. However, it is not feasible for a single operator to be available at both spots while keeping the drone within the line of sight, which is why a U-shaped transect was used in this study, with a single point for launching and landing. Many technical issues were experienced during this study, especially inflight instability, making it impossible for a single operator to simultaneously focus on immediate insect spraying and attempt to force the drone to land by hand. As the nets must be opened, a helping hand is needed to recover them if the drone lands far away from the operator.

This pilot study revealed that hobby drones equipped with homemade special nets can be used for insect sampling, but only at low altitudes (up to 20 m) due to their limited performance at higher altitudes. Compared to static ground traps (malaise traps, sweep-netting and suction traps), insect-catching drones can provide more vertical and horizontal spatial freedom to sample insects while requiring less labour. This study showed that the number of insects caught with drones decreases with altitude, and only a few specialized insects can fly at higher altitudes. Furthermore, the results confirm that the number of insects captured were affected by time of day and also by wind direction. This study also found that fixed nets were more effective at catching insects than hanging nets. An idea for future developments is

to divide the caught samples into their morphotypes³⁰ to improve the analysis in terms of population indices.

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The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies

of FAO or CIFOR/FTA.

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Invasive species management in Nepal; a pathway to sustainable forest management

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Abstract

Invasive species pose a huge challenge to forest management throughout the world. They are seriously jeopardizing forest health and disturbing the regeneration of native species and restoration of the natural ecosystems. More impacts are seen in developing countries like Nepal, where a large proportion of communities is heavily dependent on forests. Nepal's forests are managed by communities through a popular community forestry program. The management of invasive species can be economically burdensome and technically complex when implemented by communities with limited sources of income.

This study focus on the management of invasive species through participatory action research in Jalthal forest, a 6,000-ha remnant moist-tropical forested 'island' amidst a densely populated area in southeastern Nepal. This forest is an important biodiversity area with several threatened plants (*Cycas pectinata*, *Magnolia champaca*, *Rauvolfia serpentina*, *Dioscorea deltoidea*) and animals (*Manis spp.*, *Elephas maximus*, etc.). Apart from its existence value, it is an important source of different forest products and environmental services, including freshwater for about 16,000 households comprising over 80,000 people (including indigenous tribes like Rajbanshis, Meches, and Santhals) living around the forest. The forest is currently being managed by 22 community forest user groups (CFUGs). The forest has been degraded by invasive alien plant species (IAPS), particularly *Mikania micrantha* and *Chromolaena odorata*, which appear in the IUCN list of the 100 worst IAPS in the world.

The study aims to develop a participatory model for sustainable IAPS management, incorporating both scientific and traditional knowledge. First, IAPS were mapped using both satellite imagery and ground data. About 2937.7 ha were found to be infested with invasive species; among which 879 ha were considered highly infested. In these areas, different periodic removal operations were conducted, following two different methods: (i) intensive site management or (ii)

low-intensity extensive site management. Intensively managed sites were completely cleared, retaining only regenerations, whereas extensively managed sites were cleaned only around natural regeneration. After the government imposed a mandatory rule for yearly pro-poor fund allocation, CFUGs were encouraged to invest in invasive species removal, thereby creating short-term employment for the poor and highlighting the importance of IAPS management. Compost manure was produced from the biomass generated by IAPS removals, providing additional income and employment opportunities.

This paper presents the experiences of different field operations of IAPS management. Different treatments were analyzed in terms of suitability and effectiveness. Comparative economic analyses were conducted to assess the feasibility for community groups. This paper shows the importance of adopting an integrated approach for IAPS management that considers forestry, agriculture and other socio-economic activities together; that facilitates the active participation of community members; and that integrates scientific knowledge and traditional practices in an organized way.

Keywords: *invasive species, community forestry, management*

Introduction and background

Invasive alien species pose a huge challenge to forest management throughout the world. The economic cost of invasion in terms of management and adverse impacts has been estimated to reach hundreds of billion dollars (Pimentel et al. 2001). Invasive species are seriously jeopardizing forest health, disturbing regeneration and natural ecosystems. The IUCN Invasive Species Specialist Group (2000) defined alien invasive species as “an alien species which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change and threatens native biological diversity.” Unlike native species, alien invasive species spread unmanageably, propagate relatively rapidly and outnumber native species in their ecosystems because of their capacity to thrive upon foreign soil and climatic conditions (Tiwari et al. 2005). They play a key role in altering biodiversity and ecosystem functioning (Vilà et al. 2011) and are known to decrease native plant diversity (Hejda et al. 2009). They may also threaten the existence of native biota (Jauni and Hyvonen 2010). Invasions by a single species have been identified to negatively impact native species richness in a similar magnitude than land use change, the main factor causing the decline of species richness (Murphy and Romanuk 2014). On the other hand, they have also been found to increase biomass

production of the invaded area because of their competitive fast growth rate (Vilà et al. 2011).

Biological invasion has threatened biodiversity and ecosystem functions in Nepal (MFSC 2014). The emergence of new invasive alien plant species (IAPS) in agroecosystems has been considered a challenge for achieving the goals of the Agriculture Development Strategy of Nepal (MAD 2014). At least 183 exotic vascular¹ plant species including four pteridophytes² and 179 flowering plants are naturalized in Nepal. Among these, according to Shrestha (2019), 26 are invasive angiosperm species, four of which appear in the IUCN list of the 100 world’s worst invasive species (Lowe et al. 2000). The southern half of the country (Terai, Siwalik, and Middle Hills zones), which has a tropical and subtropical climate, has more IAPS than the northern half (High Mountains and High Himal) (Shrestha 2016). However, the distribution of IAPS is expanding to new regions of the country because preventive

1 A vascular plant is a plant with specialized vascular tissue, including xylem and phloem.

2 A pteridophyte is a vascular plant that disperses spores. Pteridophytes do not produce flowers nor seeds: hence, because their means of reproduction is hidden, they are sometimes called “cryptogams”.

measures have not yet been developed (Shrestha et al. 2018).

Though a wide range of impacts have been observed (MFSC 2014; Chaudhary et al. 2016), management responses are inadequate to address this emerging environmental and economic problem (Shrestha 2019). The management of IAPS can be even more economically burdensome and technically complex when it comes to community management, as communities have limited access to financial resources, generated solely through the annual allowable harvest of timber (DoF, 2004). Furthermore, scientific data appears to be inadequate to guide management and contribute to the science–policy interface (Shrestha 2019).

This study focuses on the management of IAPS through participatory action research in Jalthal forest, a 6,000-ha remnant moist tropical forested ‘island’ amidst a densely populated area in southeastern Nepal. This forest is an important biodiversity area with several threatened plants (*Cycas pectinata*, *Magnolia champaca*, *Rauvolfia serpentina*, *Dioscorea deltoidea*) and animals (*Manis* spp., *Elephas maximus*, etc). Apart from its existence value, it is an important source of different forest products and environmental services, including freshwater for about 16,000 households comprising over 80,000 people (including indigenous tribes like Rajbanshis, Meches, and Santhals) living around the forest. The forest is currently being managed by 22 community forest user groups (CFUGs). It has been degraded by IAPS, particularly *Mikania micrantha* and *Chromolaena odorata*, which are among the 100 worst IAS in the world (Lowe et al. 2000). The study aims to develop a participatory model for sustainable IAPS management, incorporating both scientific and traditional knowledge.

Description of the innovation

During the initial stage, IAPS were mapped through MaxEnt modeling³ using different indicators and criteria across the whole forest based on both satellite imagery and a field survey. The survey distinguished four degrees of invasion (high, moderate, low and non-invaded) and showed that approximately 2937.7 ha of the Jalthal forest were infested with IAPS, mainly *Mikania micrantha* and *Chromolaena odorata*, of which 879 ha were highly infested (Shrestha 2020).

Traditionally, weeding and cleaning used to be conducted annually as per the silvicultural requirements and forest management plan of CFUGs, which focused mainly on removing all weeds and bushes that impede the growth of valuable tree species. No regard was given to the long-term management or eradication of these weeds. We piloted periodic removals of IAPS in invaded areas with different intensities. One of the approaches, called intensive site management, involved complete site clearance, retaining only the regenerated seedlings and saplings. In contrast, extensive site management involved removing IAPS and other weeds only around the regenerations to rescue them from IAPS. The best time for carrying out these operations is from the start of the growing season till before the flowering season of *Mikania micrantha*. The techniques used for IAPS removal in intensive management include uprooting, stem cutting, and burning.

The IAPS biomass collected during intensive site management operations was used to produce compost, whereas the small quantity of biomass removed during extensive site management operations was not used. This biomass represented about 50 percent of the total volume of raw materials used for

3 MaxEnt stands for maximum entropy modeling, a machine-learning technique used for modeling species niches and distributions (for more information, see, e.g., Elith et al. 2010). See also: https://biodiversityinformatics.amnh.org/open_source/maxent/

compost preparation. The Indore method⁴ was adopted for compost preparation, along with traditional practices. The compost was prepared either in pits or at ground level by making four layers: (i) a foundation layer of long stems and branches to allow air circulation, (ii) a layer of forest soil mixed with a solution of cow urine (50 percent) and water (50 percent), (iii) a layer of chopped green biomass of IAPS, and (iv) a layer of cow dung. Other additives, such as bone meal, ashes, husk, and sawdust, were added to improve the quality of the compost. Hollow bamboo stems, perforated with holes, were inserted vertically from the top layer to the bottom layer for ventilation purposes, while a testing stick was inserted vertically throughout the layer to regularly monitor decomposition status. The compost was covered with black polythene to retain heat and moisture. This simple low-cost method incorporating traditional knowledge has been adopted in four CFUGs.⁵

The data for the financial analysis of compost preparation was collected from July 2020 to November 2020. A total of 20 sample plots of 10 m × 10 m were randomly laid out in the heavily infested sites. Intensive removal of IAPS was conducted in each sample plot. From each sample plot, we collected data on the biomass of IAPS, total labor needed to remove the IAPS, and time taken to remove the IAPS. We also noted and analyzed the other expenses accrued during compost preparation. However, the cost of establishing the infrastructure needed for compost preparation was not included in the analysis.

The total cost of IAPS removal following the extensive management approach was estimated through a field experience over a 20-ha area based on information collected on the total labor needed, the total time taken for removal, the name of species for regeneration, and the total number of regenerations rescued.

4 See: <https://permaculturenoosa.com.au/sir-albert-howards-indore-compost-method/> or <http://ecoursesonline.iasri.res.in/mod/page/view.php?id=149589>

5 Namely: Pathibhara Kalika, Kamaldhap, Hariyali and Tribeni CFUGs.

Results

Intensive site management

Forest areas in Jalthal have been prone to degradation due to heavy infestation by IAPS. Proper IAPS management is needed for long-term sustainable forest management, as well as to improve the livelihoods of local communities, which are heavily dependent upon forest resources. However, the management of IAPS entails high costs and requires scarce human labor. With their main income coming from the annual allowable cut of timber prescribed in the operational plan (approved by the Division Forest Office) and investment requirement in forest management, community development, and bureaucratic needs, CFUGs lack the capacity to continually invest in IAPS management in highly infested areas. In this context, compost preparation from IAPS biomass can fulfill the dual purpose of contributing to forest restoration while generating additional resources for financing IAPS management or improving livelihoods, thus ensuring sustainability. The cost of IAPS removal can be compensated by the income from compost production and sale.

An economic analysis was conducted based on the data collected in the field from July 2020 to November 2020 across the sample plots to assess the costs and benefits associated with compost preparation from IAPS biomass. In the 20 intensively managed experimental sample plots, IAPS removals generated an average of about 9,605 kg of IAPS biomass per ha (i.e. an estimated dry weight of about 4,800 kg, representing a 50-percent reduction) and required a total of 27 working days (i.e. 162 working hours based on 6 working hours per day) per ha. At a labor rate of NPR 600 per day,⁶ the total cost of IAPS removal reaches NPR 16,200 per ha for intensive site management. About 10,000kg of compost can be produced from the biomass removed from 1 ha. Detailed compost production costs, excluding the initial infrastructure cost, are illustrated in **Table 1**. Establishing the infrastructure needed for the

6 NPR stands for the Nepalese rupee. As of 13 April 2021, USD 1 = NPR 120.40.

Table 1: Detailed production costs for 10,000 kg of compost

S.No.	Expenses	Costs (in NPR)	Remarks
1	1 ha cleaning	16,200	27 working days under intensive site management
2	Total labor cost for compost preparation	60,000	100 working days at NPR 600 per day
3	Cost of raw materials and additives	15,000	Ashes, bone meal, husk, and others
4	Transportation and other	5,000	
Total costs		96,200	

compost preparation entails an additional cost of around NRS 80,000 in the first year.

At current market prices (around NPR 20 per kg), 10,000 kg of compost could generate an additional income of NRS 200,000 for CFUGs, showing that compost preparation from IAPS biomass can contribute to forest restoration while providing an economic benefit to CFUGs. As such, because the benefits outweigh the costs, forest restoration efforts can be sustained in the long run and contribute to increase income and improve livelihoods in CFUGs. Since the production cost of compost is low, it can be made available at a relatively cheap price when compared to chemical fertilizers⁷. Thus, the demand for such compost is likely to increase, provided that the quality is maintained. As the CFUGs have many infested sites, they can scale up production for increased efficiency in compost preparation.

Compost preparation also generates other indirect benefits for the CFUGs in addition to providing a direct revenue stream. For instance, income from compost preparation can be used for plantations in areas where conditions are too harsh for the establishment of natural regeneration and where natural regeneration has long been absent. In addition, the use of compost can increase soil productivity, improve texture and water-holding capacity in the long run, and decrease the dependency of local people

on chemical fertilizers, contributing to the sustainability, self-sufficiency and resilience of local farming systems.

Furthermore, the Forests Act of Nepal (2019)⁸ has made it mandatory for CFUGs to allocate at least 25 percent of their total income to forest management, and at least 50 percent of the remaining income to pro-poor related activities, women's empowerment and micro-enterprise development. CFUGs were encouraged to spend such allocated amount on IAPS management operations, which provide short-term employment opportunities and wages for poor people.

Extensive site management

In extensively managed sites, learning from field practice over a 20-ha area, cleaning 1 ha requires an average of 5 working days (i.e. 30 working hours). However, the amount of labor required increases significantly with the density of natural regeneration. The cost of *Mikania micrantha* removal in extensively managed sites is about NPR 3,000 per ha. Each year, at least three cleanings are needed to effectively control IAPS and promote natural regeneration: one at the start of the growing season, and two during the growing season. This brings the total cost to NPR 9,000 per ha per year.

⁷ The price of chemical fertilizers is in the range of NPR 18–32 in normal conditions but can sometimes rise much higher.

⁸ The Forests Act, 2019 (2076). Act No. 12 of the year 2019 (2076). Date of authentication 14 October 2019. <https://www.lawcommission.gov.np/en/wp-content/uploads/2021/03/The-Forest-Act-2019-2076.pdf>

Table 2: Detailed costs: comparison between planting⁹ and extensive IAPS removal

	Activities	Cost of planting (NPR per ha)	Remarks	Cost in extensive removal (NPR per ha)
1	Seedling production	16,000	At a spacing of 2.5 × 2.5 m ²	No cost
2	Transportation	5,000	Lump-sum	No cost
3	Site preparation	20,000-40,000	Depends upon site	No cost
5	Planting seedling	16,000	NPR 10 per seedling	No cost
6	Cleaning (first year)	30,000-40,000	Three times in the first year for plantations	9,000
	Total cost	87,000-117,000		9,000

Extensive management is considered to generate more ecological and economic benefits than planting, as shown in **Table 2** for the first year of implementation.

The above table shows an economic comparative advantage of NPR 78,000–108,000 per hectare for extensive IAPS management over plantation in the same area, provided that the area has enough natural tree regeneration potential. Therefore, it is important to properly understand the site conditions before intervening.

Moreover, extensive IAPS management also generates ecological advantages when compared to plantations. It preserves and supports higher biodiversity. Extensive IAPS removal over a 20-ha area contributed to rescuing about 12,750 individual regenerations from 58 different tree species. In addition, the introduction of exotic species without any due regard to the site condition and suitability often generates very high mortality rates, increasing the cost and limiting the success of planting operations. Conversely, extensive IAPS management facilitates the natural regeneration of already-established native species, thus minimizing costs and increasing the chances of success.

Promoting natural tree regeneration makes this approach sustainable in the long run as the obstruction of light to the forest floor by the natural regeneration inhibits IAPS growth, especially in the case of *Mikania micrantha*. This option seems to be the most effective

method of IAPS control in the long run. Its impact is already visible in the field, as rapid natural regeneration is observed in the managed sites. However, it should be noted that in areas of severe infestation where the natural regeneration has already been wiped out by IAPS and where low potential remains for natural regeneration, plantation of native species could be an appropriate option.

Conclusion

Invasive species have become a major concern for forest management and biodiversity conservation in the Jalihal forest in Nepal, in the absence of any specific operations of invasion control. Both intensive and extensive site management have their importance in IAPS removal, depending on site conditions. Extensive cleaning is recommended for sites where regeneration is present, whereas intensive cleaning is recommended for heavily infested areas.

The continuous removal of IAPS, rescuing of existing natural regeneration and continuous flow of income from compost manure in these two approaches suggests that such innovations can be sustainable in the long run, providing ecological benefits through forest restoration and biodiversity promotion, social benefits through improved collective

⁹ Planting costs displayed in Table 2 are based on the general average cost of planting timber species in lowlands of Nepal, mentioned from field experiences.



Figure 1: Above ground compost preparation in Hariyali CFUG © Sanjaya Raj Tamang



Figure 2: Compost preparation in Pathibhara Kalika CFUG © Sanjaya Raj Tamang



Figure 3: Low-intensity extensive management © Sanjaya Raj Tamang



Figure 4: Mikania removal © Sanjaya Raj Tamang



Figure 5: Raw material preparation for Composting © Sanjaya Raj Tamang



Figure 6: Severely infested area with Mikania © Sanjaya Raj Tamang



Figure 7: Teak (Exotic species) plantation inside the forest © Sanjaya Raj Tamang

action, and economic benefits by generating additional income.

Compost preparation from IAPS biomass opens up an opportunity for the sustainability of forest restoration operations in heavily infested areas. Selling the compost generates additional resources that can be used to support CFUGs' restoration activities. Employment opportunities generated by IAPS removal operations also improve the livelihoods of poor community members. The CFUGs, which have less access to external funding than protected areas, depend more heavily on their annual allowable cuts of timber as their main source of income and could adopt these methods for controlling IAPS.

Raising awareness on the impact of IAPS and the importance of simple and effective innovations such as those mentioned above is very important for the effective and timely

management of IAPS. The incorporation of these programs and their local adoption by CFUGs will help restore and preserve healthy ecosystems. Initiated in the Jalthal forest, these innovative IAPS management practices could be replicated and upscaled in other parts of the country that face similar problems.

The following recommendations emerge from this participatory research:

- Proper site study before plantation: prioritize plantation only in highly infested areas with the lowest potential for natural regeneration.
- Plantation with native species rather than exotic species.
- Periodic and concentrated cleaning with a focus on rescuing natural regeneration.

- Connect communities with forest resources and link the livelihoods of local people with forest management and restoration.
- IAPS can be controlled and generate a positive economic return if properly managed.

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Factors affecting community-based tree nurseries in the Ramu-Markham Valley of Papua New Guinea

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Abstract

Establishing community-based tree nurseries (CBTNs) in Papua New Guinea (PNG) is greatly influenced by the complexities of customary land tenure, as 97 percent of land is held under customary ownership. CBTNs are established for the purpose of reforestation or afforestation of degraded forest sites or grassland areas along the Ramu-Markham Valley. CBTNs are also established for self-utilization in agroforestry arranged garden systems, timber trees for building materials, and fuel wood, mostly for cooking, as local communities in this valley depend heavily on their environment to sustain their livelihoods.

A social survey conducted in five villages along the Ramu-Markham Valley indicated that socioeconomic and cultural aspects have a great influence on the establishment and sustenance of CBTNs within the area. This study attempted to identify the constraints affecting the development of CBTNs and tried to initiate ways to assist small-scale nursery owners and managers in acquiring the knowledge, skills and resources needed to run their own nurseries economically and efficiently. A combination of social research methods was used, including group interviews, semi-structured interviews and participant observation of meetings and activities to understand community dynamics, decision-making processes and institutional arrangements in relation to establishing CBTNs. It was observed that the success and sustenance of a CBTN depend upon the nursery's purpose, management, market opportunities and financial capabilities for continuity.

Keywords: *Community-based tree nurseries, socio-economic and cultural implications, social research methods, community dynamics.*

Introduction and background

Forest and land degradation is a worldwide challenge, and its mitigation requires multiple approaches, nearly all of which call for some level of plant establishment (Chazdon 2008, Halme et al. 2013, Laestadius et al. 2015, Lamb et al. 2005, Sabogal et al. 2015, Stanturf et al. 2014a, Stanturf et al. 2014b). Anticipated effects of global climate change suggest that future needs for restoration will increase (Stanturf et al. 2014a). In recent years, international leaders have pledged to restore millions of hectares of deforested and degraded lands, such as through the Bonn Challenge and the New York Declaration on Forests¹.

To help meet these unprecedented and ambitious commitments to forest and landscape restoration, the availability of high-quality nursery-grown seedlings will be crucial for successfully implemented forest and landscape restoration programs to create healthy, functional, sustainable and resilient ecosystems (Gregorio et al. 2015, Harrison et al. 2008). The domestication and commercialization of high-value tree products can contribute to alleviating poverty and hunger, encourage social equity and reduce environment degradation (Carandang et al. 2006) hence contributing to the achievement of the United Nations' Sustainable Development Goals (SDGs). Many large industrial nurseries in the world have the capacity to produce up to 50 million plants annually and do not necessarily contribute to community-based reforestation or community livelihood objectives (Haase et al. 2017). Establishing nurseries, including publicly-funded ones, has often a low level of priority for governments and other entities, as in the case of PNG. However, government nurseries can play a crucial role in improving the effectiveness of the forest nursery sector by diversifying their production to focus on species demanded by smallholder farmers and that cannot be supplied by individual or communal nurseries (Gregorio et al. 2015).

In PNG, where climate change and human activities such as commercial agriculture, logging, and mining cause rapid deforestation and forest degradation, applicable administrative and management mechanisms are needed to refine policy dialogues and devise implementation procedures that are scientifically grounded. Institutional arrangements and legal frameworks in the country do not provide conducive tenets to execute global initiatives to address these issues. For instance, the PNG Forest Authority (PNGFA) is currently reviewing the Forestry Act through consultation workshops to seek views and inputs from key stakeholders regarding the application of the Forestry Act (1991, amended several times)², with the view to further amending it to accommodate for emerging issues and development trends.

As a party to the United Nation Framework Convention on Climate Change (UNFCCC) and to the UN Convention on Biological Diversity (CBD), PNG is committed to taking action by integrating their goals and targets into its national development plans and to devising ways to achieve them with appropriate institutions and implementation means. The PNG national development plan, entitled Vision 2050,³ explicitly recognizes the significant role PNG's forests are playing as providers of ecosystem services and functions, as well as their contribution to local and global economies. It makes a call for all forestry stakeholders to work together on the elaboration of appropriate policies for the sustainable management of PNG's forest resources, including developing a policy framework for climate change mitigation and the carbon trade. This development plan will create opportunities for rural communities to engage in formal employment as well as improve their livelihoods.

PNG has a unique land tenure system where 97 percent of the land is under customary ownership, a type of land ownership arising from and regulated by custom in indigenous communities (Kila Pat 2003)²⁰⁰³.

1 See for instance: the Bonn Challenge (<http://www.bonnchallenge.org>), and the New York Declaration on Forests (<http://forestdeclaration.org>).

2 See: <https://www.ecolex.org/details/legislation/forestry-act-1991-lex-faoc022285/>

3 See: <https://sustainabledevelopment.un.org/content/documents/1496png.pdf>

Therefore, there are very strong synergies between sustainable forest management and local communities in PNG (Page et al. 2016). Changes in land use and forest management arise from the decisions of individual forest owners (Blanco et al. 2015). Hence understanding their decision-making processes and their implications for forest and land use changes is useful for the development of adapted policy dialogues and management programs. With the promotion of community forestry at national level, PNG is shifting from large-scale logging operations operated by preeminent companies, mostly owned by foreign investors, to smaller operations, with direct participation from the landowner indigenous communities. The PNG Government, in its efforts to promote and encourage landowner and community participation in the development, management and utilization of their forest resources, ensures that communities are actively involved in community-based forestry projects.

The Australian Centre for International Agricultural Research (ACIAR) promotes community forestry research through funding assistance and research collaboration with partner countries like PNG. ACIAR has funded a lot of collaborative research in the field of agriculture and forestry in PNG and assisted many PNG researchers through human resource development. This paper presents a two-year social-science research project incorporating mixed methods of social surveys into the baseline phase of a study designed and funded by ACIAR to examine, develop and enhance the implementation of community forestry approaches in PNG⁴. This ACIAR project, focusing on the Ramu-Markham Valley, was initiated in 2012 and has been in the implementation phase since 2014. The project aimed at enhancing the implementation of community forestry approaches in PNG through the restoration of community-owned native forests and reforestation of community-owned grasslands, referred to as community-based reforestation. During the first year of the project, a mixed social science research approach was

applied to understand the community dynamics at stake behind community forestry. This approach, facilitated by contact persons in local communities, included community gatherings and meetings along with a small livelihood survey with interested community members, based entirely on observation and dialogue.

Focusing on community-based reforestation, this paper analyzes how local communities situated in the study area responded to the project, focusing in particular on the establishment of community-based tree nurseries (CBTNs) for reforestation purposes. It describes the challenges and opportunities observed when establishing and maintaining CBTN in the target communities in the Ramu-Markham Valley. The paper further outlines how the study was conducted and discusses the small-scale participatory qualitative livelihood survey, exploring the value of community participation, as well as the socioeconomic aspects of CBTN.

Methodology

The study was conducted in five villages of the Ramu-Markham Valley (**Figure 1**): Rangianpum, Waritsian, Marawasa, Ragidzaria and Musuam. The villages are situated 10 to 15 minutes' drive from each other along the Highlands Highway. Sites were chosen based on their community forestry situations, and site inspections suggested that community forestry has the greatest potential for scaling up in these areas. This enables the project to gather data on how the communities will react to the scaling-up initiatives provided by the project, allowing us to also observe their reactions through their participation and/or involvement in CBTN.

The research was conducted during 2014 and 2015 using the community dynamics and social situation analysis study guidelines provided by ACIAR for the major project (ACIAR 2019).

Ethnography, as described by Genzuk (2003), is a social science research method that heavily relies on up-close personal experiences and possible participation.

⁴ See: <http://www.pip.com.pg/projects/completed-projects/104-enhancing-community-forestry-in-png.html>

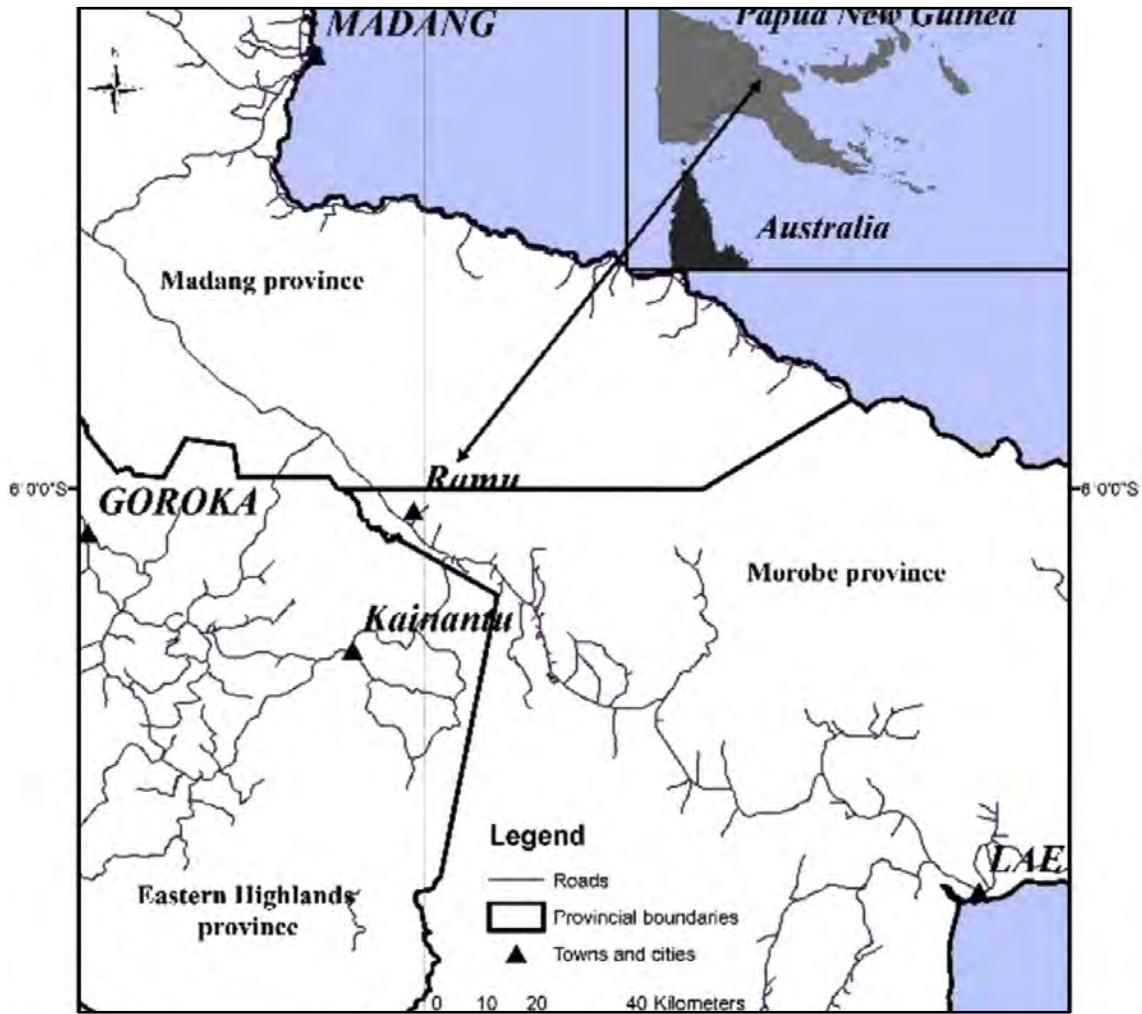


Fig. 1. The study sites in Papua New Guinea, adjacent to the towns of Ramu and Kainantu. Source: Baynes et al., 2017

The method entails informal interviews through group discussions, observations and dialogues between groups of people and/or individuals within each of the communities. It incorporates our own understanding of indigenous PNG situations to approach individuals.

Observation was the main tactic for gathering information. Being a Melanesian society, pen and paper seemed too formal, possibly raising questions that may have caused inconveniences for us as well as for the targeted communities. Hence data collected was based on hearsay and our judgement of the values and attitude of the community regarding forest use, reforestation and the establishment of tree nurseries.

Intentions of landowners to plant trees

Forest owners' attitudes towards forests and forestry, and the objectives they assign to their forests, are perhaps the most important elements affecting management decisions (Ní Dhubháin et al. 2007, Nordlund et al. 2011). They likely have substantial impacts on land use arrangements and community forestry engagements within an indigenous society such as PNG, where land is held under customary tenure, with land and forest resource intrinsic to the indigenous groups or clans.

Despite the key role of landowners in determining the expansion of forestry activities on their land, little or no attempt has been made by the national government

to characterize forest owners in PNG. For instance, a National Forest Inventory (NFI) was conducted, with the technical and financial support of FAO, to collect forest use and biodiversity data in PNG. This NFI has captured very limited information on the participation and intentions of landowners. Such large-scale studies need to recognize that forest owners each have their own unique characteristics and circumstances, rendering attempts to fully account for individual behavior infeasible (Emtage et al. 2007). To fill this gap, we tried, during this study, to identify the intentions of landowners through their participation in nursery training, nursery construction and eventually the establishment of trial planting on clan land. We also observed their participation in the project, their perceptions through dialogue, and their opinions on the CBTNs and on the forestry opportunities offered to them.

Role of community-based tree nurseries (CBTNs)

The purpose of establishing CBTNs in the study area was to observe the level of participation as well as the level of clan land user rights, and to assess the level and number of individuals who would participate in the actual CBTN program. Although CBTNs are for the purpose of seedling production, in this case, we used CBTNs to assess the participation impact from the community.

In PNG, individuals belong to a group or clan that forms the basis of land and resources ownership. Hence, this arrangement regulates and determines any activity that happens on the clan land. In that aspect, it is essential to identify appropriate protocols as to how community members would participate in the establishment of a CBTN, and the institutional arrangements on the ground that impact their participation in reforestation.

CBTNs, established in the study sites, are more adapted than larger centralized nurseries to support smallholder tree farming systems because they are located near smallholder farms, making them more convenient, safe and less costly. In this study, CBTNs were established to meet the farmer's immediate need for reforestation

and forest restoration. Furthermore, it is an observation scenario for community dynamics and institutional arrangements required in executing these activities, allowing us to understand why communities react in certain ways toward reforestation and CBTN establishment.

The concept of FLR and reforestation in PNG

Forest landscape restoration (FLR) is defined as “a process that aims to regain ecological integrity and enhance human well-being in a deforested or degraded forest landscape” (Stanturf et al. 2014b). Thus, FLR involves choices about how much and where restoration is undertaken, as well as the technical question of how to restore (Palik et al. 2000). Circumambient to this concept, this study attempted to understand how local communities can adapt FLR as a mechanism to drive CBTNs that are essential for the achievement of restoration goals.

In PNG, local people and communities engage in tree planting for land demarcation, in agroforestry systems, or within their food gardens. However, FLR is a fairly new concept to them in terms of technical aspects and technologies used. Most seedlings raised from the CBTNs were outplanted in the field chosen by the group and/or clan members. The sites were either degraded, underutilized or mountainous, mostly covered by savannah vegetation. The utilization of such sites was important for the project as it emboldened the efforts for FLR. To the landowners, the FLR concept is promising as they can engage in tree planting by utilizing their underutilized land areas; hence they were keen on the idea.

Results

Our study started with five villages, but only three villages (Rangianpum, Waritsian and Musuam) went through the whole program, as interest from participating members from two of the villages waned progressively. These three villages went through with the nursery construction and training to raise seedlings, and eventually only one village, Waritsian,

established the seedlings raised from the nursery. The socioeconomic situation on the ground, community dynamics and institutional arrangements largely explain this decreasing participation.

A significant proportion of the communities surveyed considered nursery establishment and tree planting as important livelihood options. Most communities used to plant trees for fuelwood or shade. Recently, they discovered that trees can also help to prevent the spread of fire, hence they planted vast areas of grassland, effectively suppressing grass through shading, and thus serving as fires breaks during the dry season. Village members gathered to meet with project staff and listened to the proposed idea of establishing a nursery and eventually to outplant the seedlings raised from this nursery. Unfortunately, the actual program saw decreasing interest from community members after initial participation in the social survey. Interest declined because many community members prioritized more viable economic activities such as oil palm plantation, which enabled them to generate immediate income, over participation in the reforestation and CBTN project, which offered no immediate income.

The clan plays a central role in social and economic interactions. Most members of the communities engage in activities that have interrelations with their clan and leadership ties, which they can freely engage in because, in a traditional society like PNG, clan members relate more with each other than with other clans. Most community members rely on their clan land arrangements to conduct activities such as planting trees. They actually participated in the project only when their clan had decided to allocate part of its clan land to it. Members of other clans did not participate because they did not feel that the project had to do with them. Members of a clan group withdrew from participating because they felt their clan wasn't part of the project, after realizing that other clans were taking the lead in the project.

Rangianpum

Rangianpum is a multi-clan, multi-ethnic village with about 6,000 inhabitants. The community is very active in various economic activities such as cocoa production. Rangianpum CBTN failed due to lack of participation and interest from other clans and villagers, since they had other economic activities to engage in such as cocoa farming, which was also in close proximity or adjacent to the CBTN setup. The initial community gathering saw all interested villagers, which eventually declined either due to a lack of proper community engagement by the project team or because they understood the project differently, and their perspective was not captured in this process. People who took part in the program did not take ownership of the CBTN or were simply not interested in tree farming at all.

Based purely on observation and dialogues, it appears that people in this village do understand the value of trees but prioritize cocoa and other locally produced subsistence food and cash crops for immediate income. Furthermore, the National Forest Service (NFS) manages a forestry station, about 10 minutes' drive from the village, and it is apparent that the villagers frequent the station for their forestry-related issues, probably for technical advice or even seedlings to meet their immediate forestry needs. It is dubious that this particular village, regardless of countless forestry projects and their association with NFS, has the least interest in this project.

Waritsian

Waritsian, with 3,000 inhabitants, is ideally located, close to the main road leading to the industrial township of Ramu, the Highlands region and Lae, PNG's second largest city. The village, is situated at about 1 km down the road from Rangianpum and 23 km from Ramu township, the oil palm industrial hub of the valley. Waritsian and Rangianpum have many things in common: they share a common language, have similar ancestral lineage, similar customary names, and they even share land boundaries. Further discussion revealed that historically, both communities

used to be settled together as one village near the road but later moved further out in opposite directions. Thus, both communities have clan relations with each other.

Waritsian is located in a landscape with streams, natural forests, foothills and savannah, ideal for its scenic value. From general observation and involvement with this community, the community members tend to be very respectful of their environment. There was a high level of community participation in the CBTN project. A full nursery training program was implemented successfully in this community, including nursery construction, seed collection, seed sowing, germination, transplanting, and hardening before field establishment.

Among the factors of success of the CBTN project in this community were the number of visits conducted by the project and the level of awareness associated with each visit. The local councilor was also very supportive, showing that leadership within the community is determinant to the success of the CBTN. The location of the CBTN on the councilors' clan land was also an important factor of success. The only concern here was to raise awareness in the community of the fact that the CBTN project was not restricted only to the councilor and his clan but directed at the whole community. This has been stressed, and the councilor and his clan agreed to raise the seedlings and distribute them fairly among the different clans' families.

Musuam

Musuam, with about 500 inhabitants, is by far the smallest community involved in this research for the CBTN program. The village is isolated, yet within an hour and a half's walk to the main Ramu township. Apparently, the community has been cut off from access to proper education facilities and other vital services by the overtly wide Ramu river. The community is prone to natural disasters such as landslides from backyard hilly terrains and periodic Ramu floods during the wet season.

The village comprises six major clans, most of which come from the nearby area of Gusap, while others come from Kainantu in the

Eastern Highlands province. The dominant clan, named Samban Sakan, oversees any project implemented in the community; the Samban Sakan leaders and elders need to be continuously involved for the success of the project. The lack of awareness and proper consultation prior to its establishment largely explain its failure: villagers considered the CBTN as belonging to only one person. Presumably, the choice of the religious pastor as contact person on the ground for the CBTN project was not the best choice because of his other commitments. Besides, unlike in Rangianpum and Waritsian, villagers in Musuam reside in the industrial hub of Ramu most of the time in search of employment. The seasonal jobs offered by Ramu Agri-Industrial Limited (RAIL) during harvesting and planting seasons in sugar and oil palm plantations, which address the immediate needs of the villagers, contributed to the lack of interest for and participation in the CBTN project and hence to its failure.

Discussion

Implications

PNG is a very diverse Melanesian society, with languages, customs and values differing widely across communities. Over 800 different local languages are spoken in PNG, a country of less than 9 million inhabitants, which clearly indicates the complexity of its traditional values and systems. Local communities already have their own systems in place to manage land and natural resource allocation for hunting, gardening and protection for spiritual and cultural purposes. Hence outsiders need to consider local traditional knowledge and institutional arrangements to develop strategies adapted to the local context, rather than new strategies that might not be applicable in a particular community.

Because land is highly valued and inherited traditionally from generation to generation, any development or activity introduced or to be introduced has to flow through a channel of communication and with due respect to clan elders and members. These activities can only be implemented or achieved if

a common understanding is reached by various members of the clan groups. Any disagreement will certainly create a dispute and thus hinder progress.

In all three villages, people lived in their traditional huts surrounded by clan groups in their villages. All daily activities were done in relation to customs and traditions, and people hunted where permitted and tilled also where permitted and not outside of custom. In all three villages, it was discovered that land for gardening is shared among clan members, and people only built settlements on clan land and settled by clan association.

Attempting to organize communities at a clan or multi-clan level is difficult. However, evidence shows that farmers are more comfortable with planting trees and establishing a CBTN on a land on which they have user rights and where leadership roles are honored among community members. Leadership roles in PNG are well respected and members of a clan or community members have high respect for their leaders, so members feel obliged to submit to their instructions out of respect. Therefore, in any PNG traditional society, when dealing with any form of development, including forestry and particularly nursery establishment, it is crucial to observe and identify the traditional, cultural values and systems in place to avoid disputes and facilitate successful implementation of activities.

The lack of social capital, especially of intergroup relations, also emerged as a major obstacle to CBTNs in the three villages. Extension and technical assistance were given from the research team for the initial establishment of CBTNs. Only assistance to establish CBTNs was well received, and further utilization and expansion was poor. Communities appear to have the bonding social capital to operate as small family groups, but lack the bridging social capital⁵ to work collectively with other groups in the broader community (Baynes et al. 2017). Lifting bridging social capital via a range of

extension activities may enable communities to establish and maintain CBTNs, as observed in the Philippines (Cramb 2005). However, this can be a long-term and expensive requirement.

Enabling conditions

(Baynes et al. 2017) identified three enabling conditions for CBTN establishment, each of which pose challenges: (i) target communities with a stable and firm leadership and community harmony; (ii) the presence of extension staff to help farmers to develop bridging capital via relationships with other farmers and organizations; and (iii) the supply of technical and material assistance in a do-it-yourself format, which adapts technology (e.g., via small home-nurseries) so that it can be managed by individual families.

The respective challenges are:

- i. The process of determining social harmony in communities will, by itself, raise expectations of material assistance.
- ii. Capacity development is required to bring more actors into the seedling supply chain and promote seedling supply networks.
- iii. Encouraging and assisting individual farmers may build up a clientele of champion farmers, which may inadvertently exclude other less powerful community members.

These issues are not constantly observed throughout PNG but are relevant to the study sites. In other parts of PNG, land tenure, leadership and institutional arrangements for CBTNs may be handled differently. For instance, land ownership differs across the country, as does leadership. In the New Guinea islands region, land is under customary matrilineal tenure, and thus women assume the role of landowners and leaders, whereas in the Momase region, land tenure is mainly patrilineal and men assume these roles.

5 Bonding social capital is used within a group or community whereas bridging social capital is between social groups.

Conclusion

Establishing CBTNs in the Ramu-Markham Valley (PNG) for the purpose of reforestation or afforestation of degraded forest sites or grassland areas comes with many challenges. Our study initially started with five villages, but only three villages (Rangianpum, Waritsian and Musuam) went through with the nursery construction and training to raise seedlings, and eventually only one village established the seedlings raised from the nursery. The study allowed to identify two main categories of constraints in the adoption of CBTNs. One is competition with other economic activities that provide an immediate income, namely seasonal jobs offered by the Ramu Agri-Industrial Limited (RAIL) during harvesting and planting seasons in sugar and oil palm plantations. The other derives from the links between land use and social relations in the communities. The land on which the CBTN is established may be linked to a specific clan, which requires careful involvement of clan leaders and elders. Moreover, individuals from other clans generally do not get involved unless considerable care is taken to properly involve all groups in the community.

There are opportunities to improve the process and to potentially expand CBTNs by properly considering social relations and community cohesion. In this study, CBTN establishment was used as a mechanism to strengthen community and clan members' participation in the reforestation of grasslands. Obviously, community members were more concerned about their immediate needs than participating in reforestation and tree planting activities.

Local people and communities engage in tree planting for land demarcation and agroforestry within their food gardens. Current development trends and emerging issues such as climate change pose a threat to how they utilize their land for development. It is therefore necessary to understand community dynamics and institutional arrangements in order to effectively engage communities in reforestation as well as other development activities.

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Building back for Philippine biodiversity through geotagging mother tree species for modernized and mechanized forest nurseries

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Abstract

The Philippines is considered as one of the most biodiverse countries in the world. It is listed among the world's 17 megadiverse countries and one of the 36 global biodiversity hotspots. In certain islands, flora is highly endemic. Forest is the main natural ecosystem in the Philippines and hosts numerous species of flora and fauna. However, Philippine forests are facing a large number of threats and vulnerabilities, primarily caused by anthropogenic factors such as the continuous destruction of natural habitats and unsustainable extraction of forest resources, which are contributing to the current biodiversity crisis in the country. In this context, the government has established the National Greening Program (NGP), which aims to regreen the country and cover unproductive and denuded forestlands for production and protection purposes.

The NGP promised to bring back biodiversity. However, a recent assessment from the Commission on Audit of the Republic of the Philippines (COA 2019) indicated that stakeholders have planted exotic and invasive species of trees. Instead, to preserve biodiversity, more native trees should be planted, primarily from threatened species to prevent them from extinction. Modernized and mechanized forest nurseries (MMFNs) should focus more on the production of native tree seeds, particularly those naturally occurring in the area, to preserve biodiversity. Considering the current capacities of MMFNs in the country, it will be necessary to evaluate the potential seed sizes that are compatible with the machines in the said facilities to identify possible native mother tree species within the jurisdictions of the regions with available MMFNs.

This paper reviews and analyzes current MMFN operations in the country and explores the potential of geotagging, mapping, and other available digital technologies to facilitate the identification of mother trees in the wild to improve the production of seedlings of native species.

To improve the production of the nurseries, it is worth sourcing out native tree seedlings from geotagged mother tree species. This helps build a documented and stable seed source for the nurseries and improve the quality of native seeds and seedlings they produce. In addition, geotagged mother trees can be nurtured and protected by the organizations surrounding the area with the help of the local administration.

Keywords: *Philippine biodiversity, mechanized nurseries, mother trees, native trees, geotagging*

Introduction and background

The Philippines is unquestionably one of the world's wealthiest countries in terms of species biodiversity: it is listed among the 17 world's megadiverse countries¹ and among the 36 global biodiversity hotspots.² The Philippines shelters nearly 10,000 native species of vascular plants, or around 5 percent of the world's total plant species (Pelser et al. 2011). Forests in the Philippines form a major ecosystem that contributes greatly to the rich biodiversity of the country, as well as to the livelihood of local communities. According to Global Forest Watch,³ the Philippines lost 151,000 ha (3.3 percent) of humid primary forest between 2002 and 2020. According to the Forest Management Bureau's 2019 Philippine Forestry Statistics,⁴ alienable and disposable lands account for nearly half of the total land area with forest cover.

Restoring forested landscapes is widely acknowledged as one of the most important strategies for increasing resilience and mitigating the effects of major global environmental issues, particularly climate change (Kumar et al. 2015). Good seedling quality is a key factor for the success of reforestation programs. Nurseries also

form a key component of most community forestry projects by growing seedlings (Sagwal 2020). The Philippines' National Greening Program (NGP), established in 2011 (Executive Order No. 26, s. 2011⁵), aimed to plant about 1.5 billion trees, covering about 1.5 million ha between 2011 and 2016. It also pursued sustainable development by contributing to the following national priorities: poverty reduction, food security, biodiversity conservation, and climate change mitigation and adaptation. In response to the forest cover loss observed after the six-year period, the government launched the Enhanced National Greening Program (E-NGP, Executive Order No. 193, s. 2015⁶) in 2015, which extended the period of implementation of the NGP until 2028 and expanded its coverage to the 7.1 million ha of remaining unproductive, denuded and degraded forest lands, which are more vulnerable to soil erosion, landslides and flooding. PHP 47.22 billion have been allocated between 2011 and 2019 to implement the E-NGP. However, as legislators are still skeptical about its impact, the E-NGP annual budget has been cut by half, from PHP 5.15 billion in 2018 to 2.6 billion in 2019 (COA 2019).

To intensify reforestation efforts, the government has also encouraged the production of seedlings through modernized and mechanized forest nurseries (MMFNs) that facilitate propagation of seedlings while saving labor. In MMFNs, unlike in traditional nurseries, no labor is needed to monitor different aspects of the nursery operations and control environmental factors, such

1 See: <https://www.worldatlas.com/articles/ecologically-megadiverse-countries-of-the-world.html>, and <https://www.cbd.int/countries/?country=ph>

2 See: <https://www.conservation.org/priorities/biodiversity-hotspots>, and <https://www.cepf.net/our-work/biodiversity-hotspots>

3 See: <https://www.globalforestwatch.org/dashboards/country/PHL/> (Philippines)

4 See: <https://forestry.denr.gov.ph/index.php/statistics/philippines-forestry-statistics> Land Classification from 1992-2019 (in hectares)

5 See: <https://www.officialgazette.gov.ph/2011/02/24/executive-order-no-26-s-2011/>

6 See: <https://www.officialgazette.gov.ph/2015/11/12/executive-order-no-193-s-2015/>

as moisture, humidity, and temperature. However, despite spending billions on the E-NGP, the strategy of MMFN still has not been fully implemented in all regions.

Studies showed the importance of securing high-quality forest genetic material. Specifically, Nyoka et al. (2014) found that germplasm supply systems did not efficiently meet farmers' demands and environmental expectations in terms of productivity, species and genetic diversity, and some seeds, mostly sourced from undocumented sources, are often untested for good quality. Similarly, Carandang et al. (2006) showed that smallholders tree nursery operations in the southern Philippines may have limited access to some basic resources such as propagation technologies and evidence proving the significance of using native species in the tree nurseries.

This paper reviews and analyzes the current MMFN operations in the country and explores the potential of utilizing geotagging, mapping, and other available digital technologies to facilitate identification of mother trees in the wild to improve the production of seedlings of native species.

Current use of MMFNs in the E-NGP

MMFNs in the country are currently not only raising native tree species but also housing different exotic species alongside bamboo, vegetable and fruit seedlings. During the first half of 2020, at the peak of the COVID-19 pandemic, the Department of Environment and Natural Resources (DENR) raised some 36 million seedlings of various species⁷ for the E-NGP (almost 80 percent of the target for the whole year), of which about 4.2 million seedlings were raised in its MMFNs

operating in 10 regions (PNA 2020⁸). In the National Capital Region, the MMFN utilized vegetable seedlings to ensure food security in the region (Manila Bulletin 2020⁹). In Central Luzon, another facility houses mixed seedlings of native and exotic species. During the pandemic, the DENR MMFN of Tarlac (Central Luzon region) prioritized the production of assorted vegetable seedlings for 200 local government units, people's organizations, indigenous people, religious organizations, and non-government organizations, to enhance the food security of local residents (PNA 2020).

Figures 1–7 show some of the MMFNs in action.

How to enhance the contribution of MMFNs to the success of the E-NGP

This paper suggests further exploring the following three areas of work to maximize the potential of MMFNs and enhance their contribution to the success of the E-NGP.

Use the MMFNs to promote the use of native tree species

Forests evolve over thousands of years with a mix of species and their populations reach an equilibrium with the carrying capacity¹⁰ of their ecosystem. Anthropogenic introduction of exotic and invasive species upset this equilibrium and can even drive native and indigenous species to extinction (Fernando et al. 2018). Exotic and fruit tree species and even invasive alien species are currently raised in MMFNs for economic gain (COA 2019). Peoples' organizations (POs) also tried to bargain by asking for an indigenous-to-exotic species ratio of 25:75.

7 Including forest tree seedlings, bamboo and rattan, agricultural tree crops (e.g. fruit trees, nipa palm tree, ilang-ilang, rubber, cacao, coffee), and vegetable seedlings. These various species were raised for different purposes: forest plantation, mangrove restoration, agroforestry, fuelwood production, commodity cash crops.

8 See: <https://www.pna.gov.ph/articles/1109196>

9 See: <https://mb.com.ph/2020/08/15/denr-partners-with-bpi-to-help-ensure-food-security-in-metro-manila/>

10 The carrying capacity of an ecosystem denotes the maximum population of a given biological species that the ecosystem can sustain given its available resources (e.g. food, habitat and water).



Figure 1: Red Lauan (*Shorea negrosensis* Foxw), an endemic species found in evergreen dipterocarp lowland forests in the Philippines.¹¹ © Department of Environment and Natural Resources, Region 3, Republic of the Philippines



Figure 2: Mangium (*Acacia mangium* Willd) is being sourced out. It is a fast-growing tree and a highly invasive exotic species found in tropical lowland forests in the Philippines¹² and used on plantations and agroforestry farms (Koutika and Richardson 2019). © Department of Environment and Natural Resources, Region 3, Republic of the Philippines



Figure 3: The MMFNs produce a mix of native, vegetable, and fruit bearing seedlings. At the peak of the COVID-19 pandemic, MMFNs in the country started to source out vegetable seedlings to curb hunger and improve food security.¹³ © DENR IX- Mechanized and Modernized Forest Nursery



Figure 4: DENR – MMFN, Zamboanga Del Sur (Zamboanga Peninsula Region). © DENR IX- Mechanized and Modernized Forest Nursery

11 See: [https://uses.plantnet-project.org/en/Shorea_negrosensis_\(PROSEA\)](https://uses.plantnet-project.org/en/Shorea_negrosensis_(PROSEA))

12 See: <https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/acacia-mangium>

13 See: <https://www.sunstar.com.ph/article/1856274/Zamboanga/Local-News/DENR-Agriculture-sign-vegetable-seedlings-production-accord>



Figure 5: DENR-PENRO Aklan women employees conducted a potting session on seedlings in the DENR Regional MMFN of Agoho in March 2021, as one of the activities lined up for the National Women’s Celebration Month. © Department of Environment and Natural Resources, Region 6, Republic of the Philippines



Figure 6: Conservation and Development Division Chief Officer Aida E. Esquerra inspects the okra seedlings planted in the DENR National Capital Region Mechanized and Modernized Forest Nursery in Taguig City for distribution to communities in Metro Manila. © Department of Environment and Natural Resources, Natural Capital Region, Republic of the Philippines



Figure 7: MMFN, Taguig (National Capital Region) DENR, in collaboration with the Department of Science and Technology (DOST). © Department of Environment and Natural Resources, National Capital Region, Republic of the Philippines

The E-NGP aims to preserve biodiversity. However, a recent assessment from the Commission on Audit of the Republic of the Philippines (COA 2019) indicated that exotic and invasive tree species have been raised and planted as part of the program, hampering this ambition. Several conservation groups have thus invited the government to give more importance in the program to the domestication and plantation of native tree species, especially endangered species, to improve the ecological and economic impacts of the program.

Geolocating mother trees of native species using digital technologies

The COA (2019) report also indicates that MMFN seedlings are often rejected by POs because of their poor quality and high mortality rate, which can be attributed to long and stressful transport from MMFNs to the E-NGP planting sites, as well as inappropriate soil mixtures. To improve the production of the nurseries, it is worth sourcing out native tree seedlings from geotagged mother tree

species. This can help build a documented and stable seed source for the nurseries and improve the quality of the native seeds and seedlings they produce. In addition, geotagged mother trees can be nurtured and protected by the POs surrounding the area with the help of local administrations.

Mother trees are tall old-growth trees with vast root systems connected to hundreds of other trees via a large fungi network, allowing them to share information and resources (Simard 2021).¹⁴ Gregorio et al. (2011) created an inventory and assessment of mother trees of indigenous timber species on Leyte Island in the Philippines, but there is no recent accurate record of the distribution of mother trees of native species covering the whole country. Available digital technologies can help carry out such an assessment, facilitating the successful identification of mother trees and hence the collection of high-quality seeds of native tree species for MMFNs.

¹⁴ See also: <https://time.com/6045438/finding-the-mother-tree-and-how-trees-care-for-their-saplings/>

Global Navigation Satellite System (GNSS)

Today, global navigation satellite systems (GNSS) are used in the forestry sector to determine and navigate through a dense forest canopy in real time. A GNSS can be installed in a helicopter to assist in identifying the limits of a recent or past forest fire. GNSS can also be used to locate specific trees, most likely affected by fires and other threats, including activities affecting chunks of forest (Zou et al. 2019).

Light detection and ranging (LiDAR)

LiDAR uses a pulsed laser to determine the distance of an object from the ground surface. Precise information on the object is produced if the data is collected by an airborne device that produces exact, three-dimensional data about the Earth's shape and surface properties.¹⁵ Thermal imaging photographs can provide extensive spectral information of forests, whereas LiDAR can provide information on the vertical structure of forests (Dong et al. 2014).

Geographic information systems (GIS)

A GIS is a computer system that allows the capture, storage, display and analysis of geospatial datasets, defining both the position and attributes of spatial features (Chang 2016). GIS can provide information related to timber monitoring, quality, quantity and density of the forest at a given place, as well as related to the elevation and 3D digitization of the whole site.

Manual topographical measurement (MTM)

MTM is a means of consulting and coordinating with professionals to determine local conditions (soil pH level, soil type, elevation, and temperature), as well as the diameter at breast height (DBH) and canopy size of mother trees of native species, to provide guidance for seed collection for MMFNs.

¹⁵ LiDar, which stands for light detection and ranging, is a remote sensing method that uses light in the form of pulsed laser to measure ranges to the Earth. See: <https://oceanservice.noaa.gov/facts/lidar.html>

Involving local communities and key stakeholders in seed collection and MMFN maintenance

To ensure the success of restoration projects, it is crucial to engage key stakeholders and local communities in biodiversity conservation, seed collection and the sustainable maintenance of MMFNs. Internationally, conservation and social forestry outreach nurseries have been used to accomplish a range of conservation and social forestry goals in collaboration with local stakeholders (Kimengsi and Ngala 2018). Schmidt et al. (2019) analyzed two community-based Brazilian forest restoration projects, which encouraged local community involvement to scale up the market production of high-quality native seeds for forest restoration purposes.

POs are the main implementors of the E-NGP. Providing education and capacity development to these organizations can help them empower their farmers, growers, and other workers to build knowledge on mother trees, native trees, and biodiversity conservation, among other topics.

Education and information campaigns (EIC), trainings and focus group discussions with members of the partner POs guided by experts and professionals play a critical role in developing and enhancing their advocacy in the field and ensuring the operability of the MMFNs.

As MMFNs require less labor for maintenance, social mobilization and stakeholder involvement can focus on identifying, geolocating, and geotagging mother tree of native species used for seed collection, as well as on, seed sourcing, verification and certification practices. These activities can strengthen the stakeholders' livelihoods and sense of ownership, offering them additional sources of income, job opportunities, knowledge and skills, and a stronger voice in the decision-making process. Indigenous peoples must not be left behind as they have long been strongly connected to the forests.

Civil society organizations, academia and research institutions, POs, non-governmental

organizations, local government units, indigenous communities, and other stakeholder groups play critical and complementary roles in supporting the government's restoration and reforestation efforts. These groups can forge partnerships and collaborations with the relevant national government agencies to create a technical working group (TWG) to conduct seminars, workshops, and consultations on possible ways to improve MMFN functionality and operability in connection to the greening program.

Conclusion

The E-NGP aims to preserve biodiversity. However, the COA (2019) report indicated that exotic and invasive tree species have been raised and planted as part of the program for economic gain, hampering this ambition. Ecological conservation must be balanced and harmonized with economic development. Focusing on native species must be a priority if the government focuses on enhancing the conservation of different denuded forest lands in the country and protecting remaining forests. Available digital technologies can facilitate the successful identification, monitoring, and mapping of mother trees, thus facilitating the collection of high-quality seeds of native tree species for MMFNs.

People from the organizations supporting NGP and E-NGP lack knowledge and awareness on native tree species of the Philippines. As such, education, capacity development and awareness raising can be instrumental. Intensive education and information campaigns are needed to promote the production of indigenous, native, and endemic species in MMFNs and their planting in Philippine forestlands to enrich biodiversity. As the Philippines is a global biodiversity hotspot and one of the world's megadiverse countries, any greening programs in the country will only be successful and support biodiversity if the introduction of exotic and invasive species is reduced.

Given the limited number of studies on MMFNs in the Philippines, there is a need to

ramp up research and development efforts in the areas of mother tree identification, geolocation, and seed supply systems, as well as to strengthen knowledge and information dissemination, particularly to smallholders. Additionally, transparent and complete reporting, monitoring, and evaluation of the nurseries must be carried out to further improve the functionality and operability of MMFNs.

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Advances in the wood anatomical studies with innovations in microscopy: A review

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Abstract

This paper reviews how the science of wood anatomy has evolved with the advent of different microscopic techniques. The study of plant cells can be dated back to the 17th century, with the invention of light microscopes, also referred to as optical microscopes. The invention of the scanning electron microscope (SEM) in 1937 allowed studies at greater depths of field and higher resolutions and provided the opportunity to observe 3D pictures of cells and tissues. SEMs have since been used by scientists to study the structure of vessel walls, perforation plates, vestured pits, tyloses, and other elements in wood microstructure.

One of the challenges faced by wood anatomists is the study of archeological or historical wood samples, which are sometimes fragile and damaged and do not leave much scope for thin sectioning. Another challenge is preparing thin sections of charcoal wood for identification.¹ Scientists have overcome these challenges by exploring non-invasive methods of wood identification using advanced microscopic techniques. For instance, various studies illustrate the application of X-ray computed tomography in wood research, where even a small sample can be scanned at a high resolution without destruction, making it suitable for studying historical wooden artefacts. Furthermore, reflected light microscopy has also been employed for non-invasive wood identification. Recently, 3D-reflected light microscopy has shown promising results as a tool for charcoal wood identification. This innovative non-invasive technique saves time because it does not require extensive sample preparation (thin sectioning and/or surface treatment). However, wood research needs to combine techniques as each microscopy technique has its own limitations.

Keywords: Wood microstructure, microscopy, SEM, non-invasive techniques, X-ray tomography

¹ The carbonization process modifies the structure of wood, making it difficult to identify the wood species used to produce charcoal.

Introduction

Wood has been an integral part of human lives since time immemorial. Its many applications include the construction of tools, weapons, furniture, buildings, houses, shelters, barrels, machines, railway sleepers, bridges, and ships, as well as providing an energy source (Youngs 2009). Wood is also used as a raw material in the pulp and paper industry. The wide array of wood uses makes the study of wood anatomy indispensable.

Wood anatomy has made significant contributions in resolving taxonomic conflicts, delimiting genera and subgenera, establishing evolutionary relationships among taxa and reconstructing data on past climatic conditions in dendroecology.² The study of wood microstructure is important to many scientific disciplines such as physiology, archeology, wood technology, forensics, paleobotany, systematics³, pathology and ecology.

One of the major applications of wood micro-structural studies is wood species identification when only the wood is available and morphological taxonomic investigation is not possible. Wood species identification is a prerequisite to ensure the implementation of bans on the trade of wood from endangered species, as well as the proper enforcement of trade regulations as per International Timber Trade Organization (ITTO) guidelines (Baas 1994; Wheeler and Baas 1998). Wood identification is instrumental in wood industries where suitable wood processing can only be applied if the species of wood is known as processing varies depending on wood properties (Wheeler and Baas 1998). Wood identification also helps with investigating crime scenes in forensic sciences. Accurate wood identification and the proper documentation of species used is

also required for the conservation, renovation and restoration of historical monuments, structures and wooden artefacts. When restoring damaged historical monuments and artefacts, specialists prefer to use the same wood species (Wheeler and Baas 1998), or, if unavailable, to use wood species with similar properties. Wood micro-structural studies can also provide insight into wood usage in ancient times. In India, for instance, such studies are conducted by the Archeological Survey of India (ASI)⁴ to maintain and renovate various wooden monuments across the country with the help of wood anatomists.

Wood species identification requires a detailed study of the cellular structure of secondary xylem (i.e. cell type, cell shape, arrangement and cell size) using a microscope. Ever since the discovery of microscopes, technological advancements and innovations in microscopy techniques have ushered the field of wood anatomy to new heights. For instance, innovations in microscopy made it possible to move away from the traditional 2D representations of wood microstructure and produce 3D pictures. Different microscopy techniques can be used to study wood microstructure depending on the objectives of various studies.

This paper reviews different microscopy techniques used to study wood anatomy and highlight their respective advantages and limitations. Additionally, macroscopic timber identification is also briefly described as new applications are being developed by anatomists for timber identification in the field.

Microscopy techniques used in wood anatomy

The different microscopy techniques described below are grouped under two broad categories:

- **Invasive techniques** that require sectioning the wood sample; and

2 Dendroecology is the study of ecological and environmental changes over time, as depicted in tree-rings. See: <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/dendroecology>

3 Systematics is the study of the diversification of living forms, both past and present, and the relationships among living things through time. Relationships are visualized as evolutionary trees

4 See: <http://asiegov.gov.in/>

- **Non-invasive techniques** that do not require sectioning the wood sample.

Invasive techniques

These techniques are more commonly used as they give a comprehensive description of wood anatomical features. These techniques are time-consuming and labor-intensive and require extensive sample preparation. Three commonly used techniques are described here: light microscopy (LM), transmission electron microscopy (TEM) and scanning electron microscopy (SEM).

Light microscopy (LM)

The light microscope magnifies the sample to examine its fine details. It has a light source to illuminate the sample. In compound microscopes, the light passes through a condenser lens that focuses it on a small area of the sample. This light is then collected by the objective lens, situated close to the sample, which creates a real image of the sample. This image is then magnified by a second lens or group of lenses, called the eyepiece, which generates an enlarged virtual image of the sample for the user (Murphy 2002; Holgate and Webb 2003). The magnification of the microscope is the sum of objective and eyepiece lenses and can range from x10 to x1,000. The best resolution for a light microscope, based on the numerical aperture of an objective lens, is 200 nm (Holgate and Webb 2003).

To study a wood sample using LM, blocks of wood are prepared with the proper orientation of tissues. Thin sections of wood are cut using a microtome along all three planes (i.e. transverse, radial longitudinal and tangential longitudinal). The sections are dehydrated, stained and mounted. Finally, the sections can be studied under a microscope. For digital analysis and for records, photomicrographs are taken to distinguish features. Anatomical features observed through LM are studied following the terminology published by the International Association of Wood Anatomists (IAWA) for hardwood (Wheeler et al. 1989) and softwood (Richter et al. 2004) identification.

LM generally produces 2D pictures of wood structure. Hence the 3D analysis of wood structure using LM is tedious, laborious, time-consuming and impractical as it requires serial sectioning to study vessel networks (Brodersen 2013).

Electron microscopy (EM)

The light microscope has a limited resolution because it uses visible light. To achieve higher resolution, electrons are used as the source of illumination (Williams and Carter 1996). EM can be used to reveal the ultrastructure⁵ of samples. In an electron microscope, an image viewing screen converts electron intensity into light intensity and generates a monochrome image visible to the viewer (Williams and Carter 1996). The two main types of EM are described below.

Transmission electron microscopy (TEM)

Since the 1960s, TEM has been used in wood anatomy to study the detailed ultrastructure of wood cells and cell walls. Many studies have been conducted to understand the structure of cell walls of tracheids⁶ and fibers. However, there have been limited and insufficient studies on the fundamental aspects of non-fibrous cells of xylem such as vessels, axial parenchyma and ray parenchyma⁷ (Ma et al. 2013).

In TEM, a high-energy electron beam is accelerated (typically 40–400 kV) from an electron gun. The sample must be ultrathin, i.e. electron transparent (typically <100 nm) to allow the electrons to penetrate (Reza et al. 2015; Daniel 2016). The sample transmits a stationary primary beam of electrons that is transformed into non-uniform electron

5 The ultrastructure is the architecture of cells and biomaterials, visible at higher magnifications than those typically found on light microscopes.

6 Tracheids are elongated cells in the xylem of vascular plants serving to transport water and mineral salts. Unlike vessel elements, they do not have perforation plates.

7 Parenchyma cells are wood tissue used to store and distribute carbohydrates. Not all woods have clearly distinguishable parenchyma, but most hardwoods do. The examination of parenchyma cells can be instrumental to wood species identification.

intensity. This hits the screen or electron detector and is finally converted into a monochrome image that can be perceived by human eyes. The whole path from source to screen must be in an ultra-high vacuum so that electrons are not deflected by gas molecules (Reza et al. 2015). Modern TEMs have a resolution of over 0.5 ångström⁸ and a magnification ratio ranging from x35 to x700,000 (Daniel 2016).

For TEM analysis, the sample is dehydrated by passing through a graded series of alcohol and then embedded in resin. Resin protects the fine structure of the sample and helps with cutting thin sections. Ultrathin sections are then cut using an ultramicrotome, which is usually equipped with a glass knife (Reza et al. 2015). Sections are stained to improve the contrast of the image, most commonly with potassium permanganate, uranyl acetate and osmium tetroxide. For fairly small samples like cellulose microfibrils, isolated hemicelluloses and lignin, TEM can be used without embedding and sectioning. Traditional TEM techniques only give 2D images. However, due to advances in computer applications, TEM tomography⁹ is now able to generate 3D tomograms of samples (Daniel 2016).

Scanning electron microscopy (SEM)

Both LM and TEM, with their small depth of field, present the sample in one plane at a time, thus producing a 2D image of wood (Meylan and Butterfield 1972). SEM resolution (up to 20 nm, lower than that of TEM but much higher than that of LM) and field depth (300 times higher than that of LM) makes it possible to generate 3D detailed representations of the wood ultrastructure (Meylan and Butterfield 1972; Exley et al. 1974). SEM is used to gather detailed information on the morphology, topography, composition and tissue orientation of a sample's surface (Akhtar et al. 2018; Merela et al. 2020).

In SEM, a high-energy beam of accelerated electrons (usually 10 to 40 kV) scans the

surface of the sample. These electrons interact with atomic electrons on the sample surface to produce secondary electrons. The scattered electrons are collected by the detector and an image is produced. For SEM studies, an appropriate size of cube of wood is cut, ensuring that surfaces have a clean cut to make sure no fractures or cutting lines are seen in the final image. The sample is cleaned and bleached with sodium hypochlorite and further dehydrated using alcohol. The cubes are finally mounted on sample stubs and then coated with gold in a high-vacuum evaporating unit (Jansen et al. 1998; Exley et al. 1974). A major limitation of SEM is that only the exposed surface can be examined.

SEM has long been used in wood anatomy since its invention. Various anatomical features that cannot be properly recognized by LM can be studied with SEM (Carlquist 1980). SEM is used to investigate anatomical features such as vestured pits,¹⁰ crystals, silica bodies,¹¹ tyloses,¹² perforation plates, starch grains, cell-wall structures, warts on the inner surface of walls, and helical thickenings¹³ on walls. (Stant 1973; Carlquist 1980).

Non-invasive techniques

Invasive techniques can give comprehensive information on wood anatomical structure and ultrastructure. However, they may not be adapted, for instance, to the study of archeological woods or artefacts of historical importance as it can be difficult to obtain authorization for sectioning them for microscopic investigations. Technological advancements have made it possible to study the structure of woods without sectioning.

8 1 ångström (Å) equals 10⁻¹⁰ m.

9 Tomography is imaging by sections using any kind of penetrating wave.

10 Vestured pit are pits with the pit cavity wholly or partly lined with projections from the secondary cell walls.

11 Silica bodies are spheroidal or irregularly-shaped particles composed of silicon dioxide, present in wood tissues of some species.

12 Tyloses are outgrowths of parenchyma cells into xylem vessels of secondary heartwood. They plug the vessels to protect the vascular tissue in case of drought or infection.

13 Helical thickenings are ridges on the inner face of the wood element wall in a roughly helical pattern.

Two non-invasive microscopic techniques, widely explored in wood anatomy, are discussed below.

Reflected light microscopy (RLM)

The main difference between LM and RLM lies in their illumination system. In LM, light passes through the sample, whereas in RLM, light is reflected from the surface of the opaque sample. Different techniques of surfacing and finishing on the sample surface are used to improve the visibility and detection of the anatomical features (Ruffinatto et al. 2010).

Unlike LM, RLM does not require sectioning and can be used on opaque wood samples. RLM has thus been explored for the non-invasive identification of precious wooden historical artefacts such as musical instruments, which cannot be feasibly sampled. Recently, Abdrabou et al. (2021) used RLM to identify four wood species used in ritual couches in ancient Egyptian royal tombs. RLM is gaining attention of wood anatomists as it can be directly used without extensive sample preparation. In anthracology,¹⁴ the preparation of thin sections of charcoal wood is a tedious task, explaining why 3D RLM has also been used for charcoal identification (Ruffinatto et al. 2010; Zemke et al. 2020).

However, the applicability of RLM depends greatly on the degree of visibility of anatomical features, which can help with species identification by comparing to wood anatomy databases, textbooks and IAWA lists (Ruffinatto et al. 2010; Ruffinatto et al. 2014). RLM cannot be applied on artefacts whose surfaces are generally treated and coated because this hinders the identification of anatomical features. Sometimes, very old historical structures and artefacts are deteriorated, which distorts their anatomical structure (Ruffinatto et al. 2010; Ruffinatto et

al. 2014). In such cases, some anatomical features may be recognized but wood species identification cannot be confirmed conclusively.

X-ray computed microtomography (X-ray CT)

X-ray CT is one of the non-destructive, non-invasive techniques that can be utilized to construct virtual 3D images of wood microstructure.

X-rays, which have a wavelength of less than 10 nm, can be used to illuminate and study samples. X-rays do not attenuate easily as compared to visible light and electrons. X-rays are further converted into visible light and a single projection image is captured with a CCD camera¹⁵ (Brodersen 2013; Van den Bulcke et al. 2013). As X-ray CT is a non-destructive method, the same sample can also be used repeatedly. The resolution is inversely proportional to sample width and can be up to 1 µm (Whitau et al. 2016). Unlike SEM, which examines only exposed surfaces of a sample, X-ray CT can be used to investigate the whole sample following different orientations (Brodersen 2013). Whitau et al. (2016), for example, used X-ray CT for wood species identification in archeological artefacts from Western Australia. Steppe et al. (2004) employed this method to study quantitative wood anatomical features of oak and beech woods and to explore the 3D microstructure of complex vessel networks.

Macroscopic timber identification

Illegal deforestation and the illegal timber trade pose serious and increasing threats to the world's forests. Various organizations such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)¹⁶ and the International Tropical Timber Organization (ITTO)¹⁷ are working to propose

14 Anthracology is the analysis and identification of charcoal from archeological sites and sediments, preserved after carbonization, based on wood anatomy. The carbonization process modifies the structure of wood, making it difficult to identify the wood species used to produce the charcoal.

15 i.e., a video camera containing a charge-coupled device (CCD), one of the major technologies used in digital imaging. See: https://en.wikipedia.org/wiki/Charge-coupled_device

16 See: <https://cites.org/eng/>

17 See: <https://www.itto.int/>

Table 1: A summary of advantages and limitations of different microscopy techniques.

Techniques	Advantages	Limitations	References
LM	<ul style="list-style-type: none"> Helps in study of wood microstructure Magnification- x10 to x1000 Resolution-200nm 	<ul style="list-style-type: none"> Extensive sample preparation 2D image of wood 3D analysis of wood structure is quite laborious and time-consuming as it requires serial sectioning. 	<ul style="list-style-type: none"> Holgate and Webb 2003 Brodersen 2013
TEM	<ul style="list-style-type: none"> Study the detailed ultrastructure of wood cells and cell walls. Resolution- >0.5 ångström Magnification- x35 to x700,000 	<ul style="list-style-type: none"> Extensive sample preparation 2D image of wood 	<ul style="list-style-type: none"> Ma et al. 2013 Daniel 2016
SEM	<ul style="list-style-type: none"> Generates 3D ultrastructure of wood Resolution- up to 20 nm High depth of focus 	<ul style="list-style-type: none"> Examines only exposed surfaces of a sample 	<ul style="list-style-type: none"> Meylan and Butterfield 1972 Exley et al. 1974
RLM	<ul style="list-style-type: none"> Non-destructive and non-invasive technique Can be used on opaque wood samples without sectioning 	<ul style="list-style-type: none"> Cannot be applied on artefacts whose surfaces are treated and coated Cannot be used on deteriorated old samples 	<ul style="list-style-type: none"> Ruffinatto et al. 2010 Ruffinatto et al. 2014
X-Ray CT	<ul style="list-style-type: none"> Non-destructive and non-invasive technique Rays wavelength- below 10 nm Can be used to investigate the whole sample at different orientations 	<ul style="list-style-type: none"> The resolution of 1 µm is only possible with submillimetre sample sizes 	<ul style="list-style-type: none"> Brodersen 2013 Van den Bulcke et al. 2013 Whitau et al. 2016

and implement guidelines and action plans to ensure the sustainable use of timber.

Wood identification is considered the first line of defense against the illegal timber trade as it helps forest department officials take action against timber traffickers. The identification of wood usually requires microscopic examination by trained wood anatomists, but scientists are developing methods to equip forest authorities with easily accessible and cost-effective options for quick on-the-spot macroscopic timber identification. A major advantage of these systems is that they overcome the limitations posed by laboratory-bound techniques (Tang et al. 2018).

The XyloTron system, developed by the USDA Forest Products Laboratory, enables quick on-the-spot timber and charcoal identification (Ravindran et al. 2020). The XyloTron

consists of two components: a xyloscope equipped with a camera, lens and adjustable illumination system; and a laptop equipped with wood identification software. The wood samples are dry-sanded using sandpaper, or a clean cut is made to expose the transverse surface so that the macroscopic features can be clearly seen. The xyloscope captures the images, which are then processed by computers running algorithm programs that identify the wood sample (Hermanson et al. 2013, 2019; Tang et al. 2018; Ravindran et al. 2020). These systems are preferably used to identify charcoal and wood samples up to the genus level (Ravindran et al. 2020). This is the only system for charcoal identification in the field that can be used by field personnel to verify supply chains (Ravindran et al. 2020).

MyWood-ID¹⁸ is a similar application for timber identification developed by the Forest Research Institute of Malaysia (FRIM) in collaboration with the 'Universiti Tunku Abdul Rahman' (UTAR). The application comprises two main systems: (i) an image-capturing device, i.e. a macro lens-equipped smartphone to capture macroscopic cross-sections of samples; and (ii) a cloud-hosted deep-learning model for wood species identification (Tang et al. 2017, 2018). Smartphones capture the transverse surface and upload it to the cloud server. Depending on internet connectivity, the result can be obtained within seconds (Tang et al. 2017, 2018). For ease of use, the system identifies a wood species by its common Malaysian trading name rather than its scientific botanical name (Tang et al. 2018).

These applications are limited to the on-the-spot identification of timbers and CITES-listed woods of endangered species to combat against illegal logging. Identification possibilities are usually limited to commonly used timber species in a particular country. Due to similar macroscopic features within families, certain timbers are identified only at family levels (Tang et al. 2018).

Summary and conclusion

Despite the technological advances illustrated in this paper, LM remains the most widely used and simplest method to study wood anatomical features. With burgeoning new techniques, our understanding of wood microstructure has dramatically improved, particularly thanks to new technologies allowing 3D imaging and analysis of wood microstructure. The advantages and limitations of different microscopy techniques are summarized in **Table 1**.

LM, TEM and SEM are commonly used by wood anatomists all over the world, while non-invasive techniques are quite novel and still being explored by scientists. LM gives a comprehensive understanding of the majority

of wood anatomical features, whereas SEM and TEM are used to examine the detailed ultrastructure of some wood anatomical features such as vestured pits, tyloses, and perforation plates. Although these techniques are invasive and require sectioning, they help tremendously with wood research.

Non-invasive techniques (RLM and X-ray CT) are less time-consuming and show promising results in the study of historical wooden artefacts and charcoal analysis. The non-invasive identification of wood is a boon for identifying historical artefacts, whose samples are sometimes fragile, damaged and leave little scope for thin sectioning. Literature on non-invasive techniques in the Asia-Pacific countries is quite scanty. Many countries in the region have a rich history of wooden architecture that can be studied using these techniques to obtain insights into past wood usage. X-ray CT must further be explored to gain an understanding of 3D vessel networks that can be useful in modelling transport systems in plants.

Applications are being developed for the quick on-the-spot identification of timbers based on macroscopic features. Such applications can help combat the illegal timber trade, but their usage is limited to identifying a few selected taxa. These applications must further be enhanced by adding more functions to improve image quality, such as multi-colored illumination. An international database of macroscopic features of traded timbers could be created to provide reference images to facilitate timber identification.

Different techniques can be employed depending on the specific objectives of a given study. However, each method comes with its own advantages and limitations. A combination of different microscopic techniques could be used in wood research to attain a better understanding of the microstructure and ultrastructure of wood.

18 See: <http://mywoodid.frim.gov.my/>

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Literature review of production process and self-bonding mechanisms in binderless particleboard

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Abstract

Around 80%–90% of the global particleboard production is used for furniture. Particleboards represent 57% of the global consumption of wood-based panels, and demand for particleboards is growing at a rate of 2%–5% annually. Synthetic adhesives are widely used for particleboards because of their low cost and fast drying time. However, they release gaseous formaldehydes, which are harmful to human health and the environment. Binderless particleboard is a sustainable, healthy and environmentally friendly alternative to conventional wood-based particleboards made with synthetic adhesives.

This study reviews two self-bonding mechanisms used in binderless particleboard production processes, namely hot pressing and steam injection pressing. In these self-bonding mechanisms, heat and pressure cause the partial decomposition of hemicellulose and lignin, as well as chemical reactions that create natural bonds in binderless particleboard. The characteristics of the resulting particleboard, such as density or particle size, vary according to the manufacturing process used.

Based on a review of the available literature, this study analyzes the potential of non-wood lignocellulosic materials, including kenaf, oil palm, and bamboo, as raw materials for particleboard. Kenaf cores can be used to produce low-density binderless particleboards with good sound and thermal insulation properties for building interiors. The significant lignin and hemicellulose content of oil palm make it an excellent raw material for binderless particleboard production. Bamboo binderless particleboard, produced with waste from the bamboo processing industry, is a value-added product that can contribute to achieving net zero carbon emissions.

Keywords: *binderless particleboard, production process, self-bonding mechanism*

Introduction and background

Around 80%–90% of particleboard production is used for furniture (Oliveira et al. 2016). Particleboards represent about 57% of the total consumption of wood-based panels, and demand for particleboards is growing at a rate of 2%–5% per year (Tajuddin et al. 2016). This growing demand for wood and wood panels increases pressure on forest resources. Particleboards can be manufactured from scrap wood, recycled wood, short rotation species, and other alternative biomass resources, which are currently underutilized. Optimizing the use of these alternative biomass resources could add value to formerly underutilized species and contribute to reducing pressure on forests.

Synthetic adhesives are widely used in particleboard production because of their low cost and fast drying time (Hashim et al. 2011a). Urea–formaldehyde (UF) and phenol–formaldehyde (PF) resins are the most commonly used synthetic adhesives (Hashim et al. 2005). The main advantage of UF resin, which is the most popular interior adhesive in the wood composite industry, is its low cost (Hashim et al. 2005; Laemsak and Okuma 2000). Despite their affordability and small proportion (8%–10%) of the total weight of the oven-dry raw material, UF resins account for up to 60% of the total cost of the final product. In addition, synthetic adhesives release gaseous formaldehydes, which are harmful to both human health and the environment as they contaminate indoor air and cause sick building syndrome.¹ (Halvarsson et al. 2009; Hashim et al. 2010).

Binderless particleboard is a sustainable, healthy and environmentally friendly alternative to conventional wood-based particleboards made with synthetic adhesives. This study reviews two self-bonding mechanisms used in binderless particleboard production processes, namely hot pressing and steam injection pressing. In these self-bonding mechanisms, heat and

pressure cause the partial decomposition of hemicellulose and lignin, as well as chemical reactions that create natural bonds in binderless particleboard. The characteristics of the resulting particleboard, such as density or particle size vary according to the manufacturing process used.

Binderless particleboards can also facilitate the use of non-wood lignocellulosic materials, such as kenaf (*Hibiscus cannabinus* L), oil palm (*Elaeis guineensis*), and bamboo (various species), further reducing pressure on wood demand and timber extraction from forests. Based on a review of the existing literature, this paper analyzes the potential of various non-wood lignocellulosic raw materials, chemical components, production processes, and self-bonding mechanisms in the production of binderless particleboards.

Binderless particleboards: self-bonding mechanisms

Heat and pressure, when applied to lignocellulosic raw materials, provoke the partial degradation of cellulose and hemicellulose, as well as chemical reactions that create natural bonds in binderless particleboards (Okuda et al. 2006a; Hashim et al. 2011a; Zhang et al. 2014; Hill 2006; Xu et al. 2006; Inoue et al. 1993; Rowell and McSweeney 2008; Tshabalala et al. 2012; Cristescu and Karlsson 2013; Fahmy and Mobarak 2013). Chemical constituents such as lignin, cellulose, hemicellulose, starch, and sugar are important bonding agents in binderless particleboards. As a complex phenolic amorphous polymer in cell walls, lignin can act as a binding agent in particleboards. The decomposition of lignin and hemicellulose generates acetone, as well as organic and furfural acids that can further polymerize and act as binding agents, as illustrated in **Figure 1**. According to Quintana et al. (2009), covalent bonds in lignocellulosic raw materials can occur by molecular mechanical bonding when the lignin is softened and distributed. This self-bonding mechanism occurs when the surface of the raw material and lignin are bonded together under high pressure.

¹ Sick building syndrome (SBS) is a condition whereby people suffer from illness symptoms or become infected with a chronic disease from the building in which they work or live.

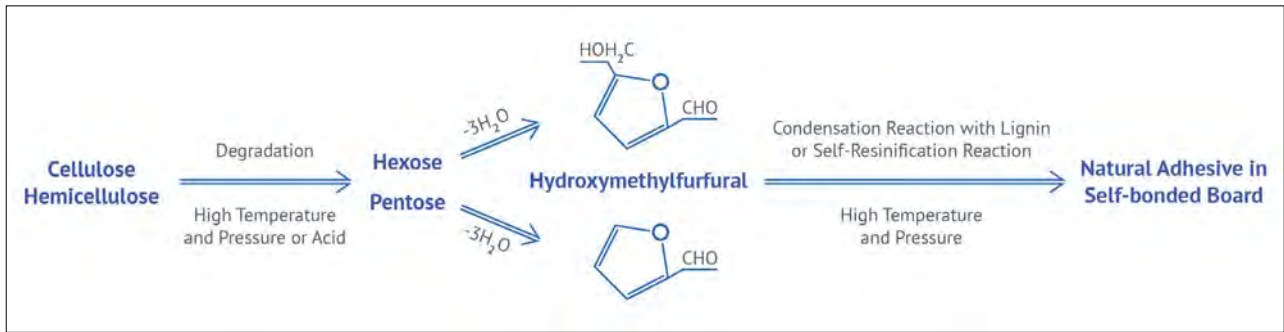


Figure 1: Self-bonding mechanisms in binderless particleboards. Adapted from Zhang et al. 2014

Different parameters affect the self-bonding mechanism as well as the resulting properties of the corresponding particleboard, including temperature, pressure, and time and particle size. According to Tajuddin et al. (2016), the dimensional stability² of the particleboard is only affected by pressing pressure, while water absorption (WA) depends on pressing temperature, pressure, and time. Li and Liu (2000) argue that pressing time has no significant effect at high pressures, whereas according to Zhou et al. (2010), the longer the pressing time, the higher the IB strength of the resulting particleboard.

Particle size and geometry also affect the mechanical properties of the particleboard. Previous studies (Munawar et al. 2007; Hashim et al. 2010) showed that smaller particles are associated with higher IB values. Smaller particles also generate better dimensional stability and a smoother surface in binderless particleboards (Mobarak et al. 1982; Hashim et al. 2010). However, smaller particles, especially when used in powder form, may require more energy and be more difficult to handle during the production process (Okuda and Sato 2004) because it takes extra time during the selection process and affects the area of bond contact in the board.³

The following sections present two self-bonding mechanisms commonly used to produce binderless particleboards.

Hot pressing

Some lignocellulosic materials that can be used to produce binderless particleboards through hot pressing, such as with a hydraulic hot press, are listed in **Table 1**.

Hot pressing, when the temperature and pressure are sufficient, activates chemical components in the raw material (Tajuddin et al. 2016). It causes lignin, cellulose, or hemicellulose to melt on the cell surface and form a natural bond (Hashim et al. 2011b). It is necessary to apply sufficient heat and pressure to melt lignin in all parts of the particleboard, allowing an even distribution of lignin in the lignocellulose feedstock during the manufacturing process (Mancera et al. 2008; Zhou et al. 2010). The higher the temperature, the higher the particleboard's modulus of rupture (MOR) and internal bond (IB) strength, and the lower the thickness swelling (TS) and the WA ratio, which reflect dimensional stability (Boon et al. 2013). However, the temperature should be limited to 200°C to avoid burning and reduce energy consumption. According to Hidayat et al. (2014), the optimum water content is 8% of the raw material in volume because higher water content can moisten the raw material and adversely affect particleboard's dimensional stability.

² Dimensional stability reflects the changes occurring in the dimensions of a particleboard as a result of variations in moisture and water content.

³ Strands are thinner, longer, and have a larger contact area with a better glue line, which leads to better strength characteristics. The roughness value of strands is higher because strands are coarser and have a rigid structure of vascular bundles.

Table 1. Non-woody lignocellulosic raw materials that can be used to produce binderless particleboards

Resources	Manufacturing process	Other treatments	References
Plantain	Hot pressing	Laccase	Álvarez et al. (2011)
Wheat Straw	Hot pressing	Fenton's reagent	Halvarsson et al. (2009)
Miscanthus sinensis	Hot pressing	Steam explosion/ <i>lignin addition</i>	Velásquez et al. (2003a)
Banana Bunch	Hot pressing	Steam explosion	Quintana et al. (2009)
Seed Cake	Hot pressing	N/A	Hidayat et al. (2014)
Cotton stalks	Hot pressing	N/A	Fahmy and Mobarak (2013)
Bamboo	Hot pressing	Steam explosion	Shao et al. (2009)
Kenaf core	Hot pressing	N/A	Okuda et al. (2006a), Okuda and Sato (2004)
	Steam injection	N/A	Xu et al. (2006)
<i>Vitis vinifera</i>	Hot pressing	Steam explosion /alkalin lignin	Mancera et al. (2011)
<i>Cynara cardunculus</i>	Hot pressing	Steam explosion	Mancera et al. (2008)

Source: Zhang et al. (2014).

Steam injection pressing

Steam injection pressing is a new process for particleboard production developed in recent years. The process performs significantly better than traditional hot pressing, generating higher IB and lower TS (Widyorini et al. 2005a, 2005b, 2005c; Xu et al. 2003, 2005; Li et al. 2011). Widyorini et al. (2005b) showed in particular that dimensional stability is higher in binderless particleboards produced through steam injection pressing compared to traditional hot pressing. The TS obtained with steam injection pressing is 25% less than that obtained through traditional hot pressing (150–200%).

The mechanical properties of particleboards produced through steam injection pressing under various conditions are illustrated in **Table 2**, while a comparison of the mechanical properties of particleboards obtained through steam injection pressing and traditional hot pressing is provided in **Table 3**.

Binderless particleboards: possible raw materials and their potential

Binderless particleboards can be produced from five types of natural fibers:

- Lignocellulose material from wood (Anglès et al. 1999, 2001; Miki et al. 2003);
- Non-wood lignocellulosic materials such as kenaf (Okuda and Sato 2004, 2006; Widyorini et al. 2005b; Xu et al. 2006; Aisyah et al. 2013), oil palm (Suzuki et al. 1998; Hashim et al. 2010, 2011a, 2011b, 2012; Baskaran et al. 2012), and bamboo (Widyorini et al. 2011; Suhasman et al. 2010, 2013);
- Plantation waste such as leaves and leaflets, rachis, leaf sheaths, date palm fibrils (Saadaoui et al. 2013), banana bunches (Quintana et al. 2009), durian peels (Charoenvai 2013), coffee husks (Milawarni et al. 2019), and empty fruit bunch from oil palm (*Elaeis guineensis* Jacq) (Cahyana 2014; Lestari 2013);
- High-fiber agricultural waste such as wheat and rice straws (Luo and Yang 2011, 2012);

Table 2. Mechanical properties of particleboards produced by steam injection pressing under various conditions

Raw material	Kenaf core	Kenaf core	Sugarcane Bagasse (leather)	Kenaf Core (Pre-treatment long cooking time)
Steam injection (MPa)	1	1	1	0.8
Time (minutes)	10–15	7–10	6	10
Target density (g cm ⁻³)	0.7	0.1–0.3	0.8	0.5
Density g cm ⁻³)	0.65	0.15–0.25	0.75	0.44–0.57
IB	0.6	0.15	0.2	0.43
MOR (MPa)	16	2	5	12
MOE (MPa)	3	0.5	1	1.7
Reference	Xu et al. 2003	Xu et al. 2004	Widyorini et al. 2005b	Xu et al. 2006

Note: MOE stands for modulus of elasticity.

Source: Pintiaux et al. (2015)

Table 3. Comparison of the performance of steam injection pressing and traditional hot-pressing methods

References	Process	Density (g cm ⁻³)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS (%)	WA (%)
Okuda and Sato 2004 (Inti Kenaf + Furfural)	Hot pressing (5.3 Mpa)	1.0	9.3	5500	5.70	19.6	40.9
Luo and Yang 2011 (Wheat straw)	Steam injection pressing (< 3.6 Mpa)	1.0	19.80	-	0.26	-	61.0

- Industrial waste such as used paper (Li and Liu 2000) and several other materials (Velásquez et al. 2003a, 2003b; Hunt and Supan 2006; Zhou et al. 2010; Marashdeh et al. 2011; Xie et al. 2012; Kurniati et al. 2015).

The advantages and disadvantages of using natural fibers as raw materials to produce binderless particleboards are illustrated in **Table 4**.

The chemical content of various lignocellulosic materials that can be

used to produce sustainable binderless particleboards are provided in **Table 5**.

The following sections illustrate the performance of various raw materials for binderless particleboard production.

Kenaf (*Hibiscus cannabinus* L)

Kenaf cores can be used to produce low-density binderless particleboards with good sound and thermal insulation properties for building interiors. According to Xu et al. (2004), Kenaf core binderless particleboards have suitable mechanical properties, achieve

Table 4. Advantages and disadvantages of natural fibers

Advantages	Disadvantages
Production uses renewable resources, requires little energy, and generates low CO ₂ emissions	Variable quality, influenced by weather and age
Friendly processing, no wear and tear to engine and no skin irritation. Avoid noxious formaldehyde emissions.	Poor moisture resistance, which causes swelling of fibers
Production with low investment at low cost	Restricted maximum processing temperature
High electrical resistance	Lower durability
Good thermal and acoustic insulating properties	Poor fire resistance
Biodegradable	Hydrophilic – low wetting with hydrophobic polymers

Source: adapted from Sreekumar (2008).

Table 5. Chemical content of various lignocellulosic materials

Fibers	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)	Reference
Flax	2.2	71.0	18.6–20.6	1.7	Li et al. 2007
Jute	12.0–13.0	61.0–71.5	13.6–20.4	0.8	
Kenaf	15.0–19.0	31.0–57.0	21.5–23.0	2.0–5.0	
Sisal	7.0–11.0	47.0–78.0	10.0–24.0	0.6–1.0	Bismarck et al. 2005
Coir	40.0–45.0	32.0–43.0	25.0–25.0	2.0–10.0	
Coconut Husk	36.7–45.1	51.1–48.2	67.6–58.8		Panyakaew and Fotios 2011
Bagasse	19.2	56.9	76.3		
Date Palm	31.9	50.6	8.1	6.8	Saadaoui et al. 2013
Durian Fiber	10.1		48.6	3.9	Charoenvai 2013
<i>Miscanthus sinensis</i>	19.9	42.6	10.1	0.7	van Dam et al. 2004
Betung Bamboo	30.6	46.2	16.3	-	Suhasman et al. 2013
Banana Bunches	5	63	10	0.8	Mohanty et al. 2000
Oil Palm	17.2	60.6	32.5	5.4	Hill and Abdul Khalil 2000

Note: This table presents percentages in weight.

Source: Tajuddin et al. (2016)

the same thermal conductivity values as traditional insulating materials, and have a high sound absorption coefficient.

Okuda and Sato (2004) examined the properties of binderless particleboards produced from kenaf cores through

hot pressing under a variety of different manufacturing conditions. They showed that the optimal pressure, temperature, and time were 5.3 MPa, 180°C, and 10 minutes respectively for a particleboard density of 1 g cm⁻³. Okuda and Sato (2006) further showed that binderless particleboards from

Table 6. Chemical composition of different parts of the oil palm tree

Parts of oil palm	Extractive ⁴ content (%)	Chemical composition (%)		Lignin
		Holocellulose	Alpha cellulose	
Bark	10.00	77.82	18.87	21.85
Leaves	20.60	47.7	44.53	27.35
Fronde	3.50	83.13	47.76	20.15
Mid-part of trunk	14.50	72.6	50.21	20.15
Core-part of trunk	9.10	50.73	43.06	22.75

Note: This table presents percentages in weight.

Source: Hashim et al. (2011b).

kenaf cores are more water-resistant than particleboards manufactured with synthetic adhesives. Okuda et al. (2006a, 2006b) also studied the chemical properties of binderless particleboards obtained under various pressures and temperatures. They showed that the chemical changes caused by the degradation of lignin and hemicellulose during hot pressing can accelerate the production process.

Xu et al. (2003) compared the mechanical properties of binderless particleboards from kenaf cores (density 0.5 g cm⁻³) obtained through steam injection pressing or traditional hot pressing. The results showed that steam injection pressing performed better in terms of internal bond strength (IB = 0.43 MPa) and thickness swelling (TS = 11%) than the traditional hot pressing method (IB = 0.09 MPa; TS = 169%), but the resulting durability value did not meet the Japanese JIS-A5908 standard (JSA 2003). Widyorini et al. (2005b), studying the chemical properties of binderless particleboards from kenaf cores, found that hot steam injected with a pressure of 0.6 to 1 MPa for 7 to 20 minutes can increase and accelerate the degradation of lignin, cellulose, and hemicellulose compared to the traditional hot pressing method.

Oil palm (*Elaeis guineensis*)

In Indonesia, the area devoted to oil palm plantation has increased from about 200,000 hectares in 1980 to almost 15 million hectares in 2019 (FAOSTAT; **Figure 2**). This rise in oil palm plantation generates increasing amounts of waste that can be used to produce binderless particleboards.

As illustrated in **Table 6**, chemical composition varies between different parts of oil palm. The high content of holocellulose⁵ and alpha cellulose in each part provides the chemical components needed for the production of binderless particleboards. Abdul Khalil et al. (2006) found that oil palm stems have a high content of holocellulose, amounting to 73.06%.

The differences in starch and sugar content in oil palm parts (Hashim et al. 2011b) are shown in **Table 7**. Suzuki et al. (1998) studied the production of binderless particleboards from palm leaf pulp through hot steam injection. The mechanical strength of the resulting binderless particleboard complies with the JIS-A5908 standard and has a dark brown color with a smooth surface. Hashim et al. (2010, 2011b, 2012) studied the production of binderless particleboards from different parts of oil palm (e.g. bark, leaves, middle part, and core part of the stem): all parts are high in lignin, starch, sugar, and holocellulose

4 Extractives form a category of diverse chemical compounds with low to moderately high molecular weights that are, by definition, soluble (extracted) in organic solvents or water.

5 Holocellulose denotes the total polysaccharide fraction in wood, straw, and other lignocellulosic materials, including cellulose and all hemicelluloses.

Table 7. Starch and sugar content of different parts of the oil palm tree

Oil palm tree by part	Starch (%)	Sugar composition (mg ml ⁻¹)				Total sugar (mg ml ⁻¹)	Total sugar phenol sulfuric acid (mg ml ⁻¹)
		Glucose	Xylose	Arabinose	Fructose		
Bark	4.14	3.53	6.55	1.15	0.22	11.42	13.67
	(0.30)	(0.61)	(3.25)	(0.57)	(0.38)		(0.90)
Leaves	2.53	2.17	3.79	1.70	–	7.66	9.29
	(0.12)	(0.17)	(3.72)	(0.69)			(0.39)
Fronds	3.10	5.31	6.50	1.33	–	13.14	14.29
	(0.09)	(0.95)	(3.42)	(0.49)			(2.74)
Mid-part of trunk	12.19	5.97	6.61	1.09	–	13.67	14.45
	(0.63)	(0.65)	(3.51)	(0.55)			(1.02)
Core-part of trunk	17.17	6.55	6.20	1.31	0.04	14.06	16.56
	(0.40)	(0.58)	(3.71)	(0.60)	(0.07)		(1.15)

Note: Values between parentheses are standard deviations.

Source: Hashim et al. (2011b).

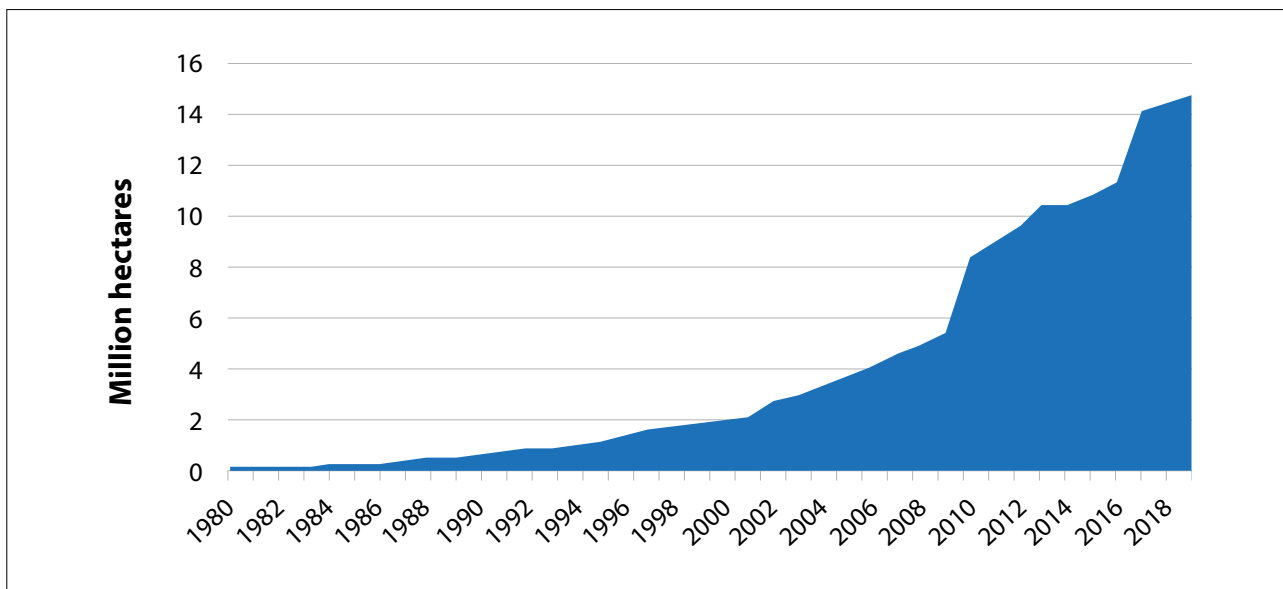


Figure 2: Evolution of Indonesian oil palm plantation area 1980-2019 (million hectares). Source: FAOSTAT⁶

content. They show that the particleboard's properties meet the JIS-A5908 standard and that dimensional stability is high due to pre-treatment.

Saadaoui et al. (2013) studied binderless particleboards produced from four parts of different oil palm species through hot pressing. Particleboards from oil palm fibrillin show high internal bond strength and low water absorption because fibrillin has a high lignin content and a high water resistance.

6 See: <http://www.fao.org/faostat/en/#data/QCL> [accessed 1.09.2021].

Table 8. Comparison of mechanical properties of particleboards obtained from different raw materials

Reference	Raw material	Density (g cm ⁻³)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS (%)	WA (%)
Okuda and Sato 2004	Kenaf core	1.0	9.3	5500	5.7	19.6	40.9
Widyorini et al. 2011	Betung bamboo	0.9	9.2	1.94	0.26	5	29
Hashim et al. 2012	Oil palm bark	0.8	10.86	-	0.53	20	-

Notes: MOR (modulus of rupture); MOE (modulus of elasticity); IB (internal bond strength); TS (thickness swelling); WA (water absorption).

Bamboo

According to Widyorini et al. (2011), particleboard production from bamboo particles, a byproduct of the bamboo processing industry, can contribute to achieving net zero carbon emissions. Suhasman et al. (2010) produced particleboards from Andong bamboo (*Gigantochloa pseudoarundinaceae*) using three types of pre-treatment, namely: (i) boiling water for 30 and 60 minutes, (ii) oxidation using hydrogen peroxide, and (iii) a combination of boiling water for 30 minutes and oxidation using hydrogen peroxide. The results show that the oxidation pre-treatment produces better results than the boiling water pre-treatment. The dimensional stability and MOE of particleboards pre-treated through oxidation are excellent, superior to those of conventional particleboards using melamine–formaldehyde synthetic adhesives. The oxidation treatment strengthens the bond structure between bamboo particles, allowing the formation of cross-links, esterification, hydrogen bonds, lignin and furfural condensation, resulting in a high MOE value (Suhasman et al. 2010).

In Betung bamboo (*Backer dendrocalamus Asper* or giant bamboo), holocellulose represents more than 50% of the total chemical constituents in volume (Dransfield and Widjaja 1995). Changes in the chemical structure of the bamboo particles can increase the particleboard's dimensional stability. Widyorini et al. (2011) studied the effect of particle size and moisture content on the physical and mechanical properties of binderless particleboard produced from

Betung bamboo under two moisture content (MC) conditions, namely air-dried and MC of 20±2%. The results show better mechanical properties and a higher dimensional stability for MC 20±2% than for air-dried particleboards.

Suhasman et al. (2013) compared the production of binderless particleboards from three Sulawesi bamboo species⁷ using hot pressing. They showed that the best results were obtained with Betung bamboo due to chemical differences, in particular in lignin content, across species. However, even with Betung bamboo, the particleboard's physical and mechanical properties did not meet the JIS-A5908 standard.

A comparison of the mechanical properties of kenaf, oil palm and bamboo particleboards

The mechanical properties of particleboards obtained from Kenaf cores, Betung bamboo or oil palm bark are compared in **Table 8**.

Other lignocellulosic materials

Charoenvai (2013) focuses on the insulation properties of binderless particleboards with durian peel powder replacing formaldehyde-based resins as an adhesive. The results show physical properties and thermal conductivity complying with TAPPI standards.⁸

7 Namely: Parrang bamboo (*Gigantochloa ater*), Betung bamboo (*Dendrocalamus asper*), and Tallang bamboo (*Schizostacyum barcahykladum*).

8 See: <https://www.tappi.org/Publications-Standards/Standards-Methods/>

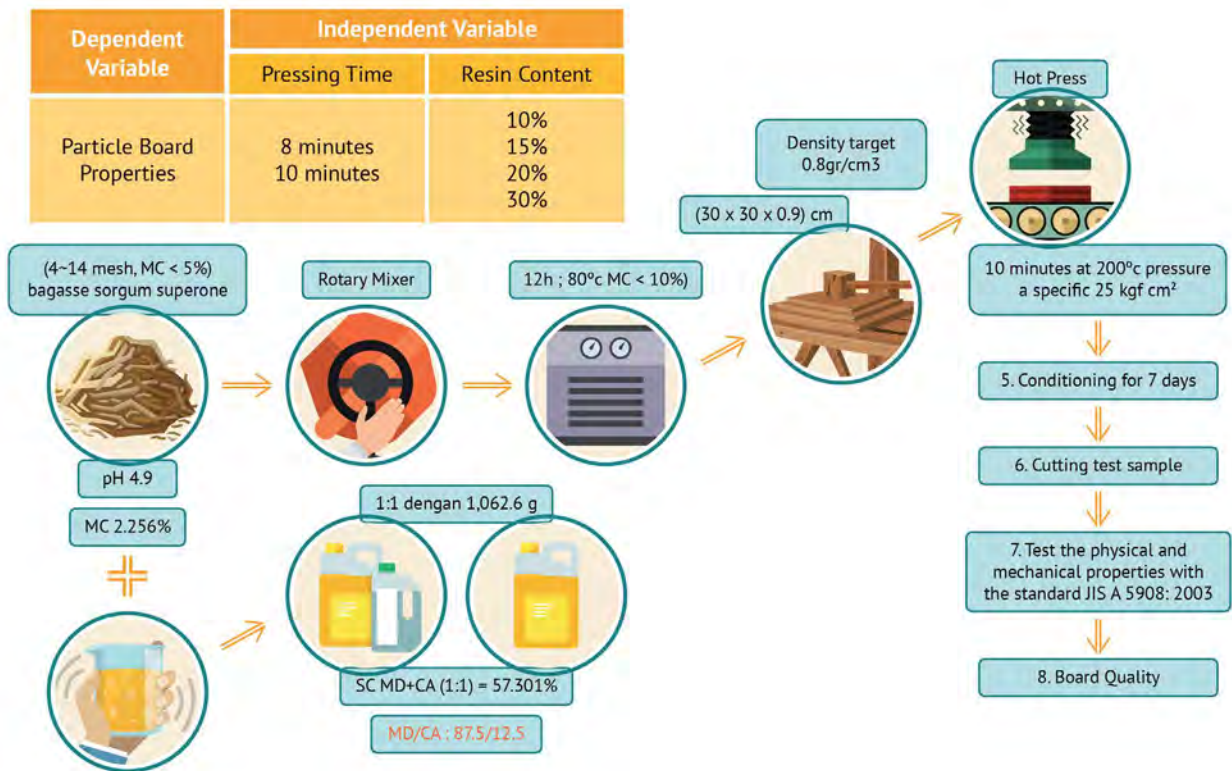


Figure 3: The process of using a combination of citric acid and maltodextrin as a bonding agent in sorghum bagasse particleboard

Source: Authors

Luo and Yang (2011, 2012) studied the effects of two pre-treatment methods (steam-blast method and liquid hot-water pretreatment) on the properties of the raw material (wheat straw or rice straw). Both methods appear to increase the degradation of chemical components. Kurniati et al. (2015) examined the effect of hot pressing at various temperatures⁹ on the physical and mechanical properties of castor beans (*Ricinus communis*). Good physical and mechanical properties¹⁰ were obtained with a binderless particleboard from jatropha (*Jatropha curcas*) seeds hot-pressed at a temperature below 170°C.

As illustrated in **Figure 3**, binderless particleboards can also be manufactured using high-fiber agricultural waste instead

of formaldehyde synthetic adhesives. For instance, a combination of citric acid (CA) and maltodextrin (MD) in equal proportions¹¹ can be used to produce sorghum bagasse particleboards (Syamani et al. 2020). The sorghum bagasse was hot-pressed¹² with various proportions of CA:MD adhesive content¹³ to produce a particleboard with a target density of 0.8 g cm⁻³. The particleboard’s MOR and MOE fulfilled the standard of type 8 particleboard according to

9 150, 160, 170, 180, and 190°C.

10 MOR = 8.17 MPa; MOE = 244.4 MPa; IB = 0.28 MPa; water absorption: 76.5%; thickness expansion: 29.5%.

11 At a volume ratio of 1:1 (CA:MD).

12 At a temperature of 200°C and a pressure of 5 MPa over 8 to 10 minutes.

13 15%, 20%, 25%, and 30% respectively. The CA:MD adhesive mixture was most efficient as binding agent at a content of 30%.

the JIS-A5908 standard. The particleboard's physical properties were excellent.¹⁴

Conclusion

Self-bonding mechanisms such as hot pressing or steam injection pressing are used to produce binderless particleboards, in which heat and pressure cause the partial decomposition of hemicellulose and lignin, as well as chemical reactions that create natural bonds, replacing synthetic adhesives in binderless particleboards. Binderless particleboards reduce the use of chemical adhesives, providing a sustainable, healthy and environmentally friendly sustainable alternative to conventional wood-based particleboards.

This study also highlights the potential of previously underutilized non-wood lignocellulosic materials for binderless particleboard production. Kenaf cores can be used to produce low-density binderless particleboards with good sound and thermal insulation properties for building interiors. The significant lignin and hemicellulose content of oil palm make it an excellent raw material for binderless particleboard production. Bamboo binderless particleboards produced with waste from the bamboo processing industry is also a value-added product that can contribute to achieving net zero carbon emissions.

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14 For instance, particleboard thickness swelling was under 12%. The bonding strength of the CA:MD combination exceeded 0.3 N mm⁻², which corresponds to the minimum requirement for type 18 particleboards based on the JIS-A5908 standard (Syamani et al. 2020).

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Corrigendum

Updated on 30 Nov 2021

The following corrections were made to the PDF after it went to print.

Page	Location	Text in printed PDF	Text in corrected PDF
89	Author list	Shahrukh Kamran, Wiebke Ullman, Andreas Linde	Shahrukh Kamran, Andreas Linde, Wiebke Ullmann
90	Introduction	(Dronesvilla 2020; Perkins 2018)	(Dronesvilla 2020; Perkins 2018),
99	Fig. 12	Figure 12. Number of insects caught by all three methods in diverse habitats Source: Authors	Figure 12. Number of insects caught by all three methods in diverse habitats Note: the numbers for grassland, rapeseed and wheat have double as many transect line than those for hedges. Source: Authors
103	Conclusion	For the locust study, scientists designed special net carrying drones to catch locust swarms. This may provide food security in terms of both locusts as food and securing crops. In a similar study, scientists used drones to study the dispersal patterns of ballooning spiders ²⁹ (Cho et al. 2018).	In future, I believe that ecological researchers could get benefit from improvised drone-net designs that will be able to catch locust swarms. Catching destructive swarms will help with pest control and securing crops in many Asian and African countries. Hence, it could improve food and economic security in such regions, moreover caught locusts (as superfood) could possibly end up in local bushmeat markets and street food.

Other modifications:

Pg 94, Fig. 5

- Legend, captions and labels in figure have been improved for readability (no changes in content)

Pg 97, Fig. 8

- Removal of upper title “Cumulative no. of insects (1319 Individuals) Caught at the ground level and at five varied altitudes (hedges excluded)”
- Typo correction on point over 4m, from 250 to 259

Pg 98, Fig. 9

- Removal of upper title “Cumulative no. of insects (885 Individuals) 576 (Malaise trap - MT), 220 (Fixed net) and 89 (Hanging net) respectively”

Pg 98, Fig. 10

- Removal of upper title “Cumulative no. of insects (885 Individuals) 576 (Malaise trap - MT), 220 (Fixed net) and 89 (Hanging net) respectively”
- Addition of 1 point (green cross + at H_5)

Pg 103, Conclusion

- In the change mentioned in the above table, please note that we also deleted the content of the footnote #29 which stated: “A process that enables some species of spiders to glide through air to disperse spatially by using their silk stands charged due to an atmospheric electric field (evidence at up to 5 km altitude and on ships in mid- ocean).”

Pg 105, Reference List

- Deletion of this reference: Cho M, Neubauer P, Fahrenson C and Rechenberg I. 2018. An observational study of ballooning in large spiders: Nanoscale multifibers enable large spiders’ soaring flight. PLOS Biology 16(6): e2004405.
<https://doi.org/10.1371/journal.pbio.2004405>

WORKING PAPER • 10

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This publication assembles selected papers prepared by youth from the Asia-Pacific region on innovative forest technologies and their contribution to sustainable forestry and sustainable forest management. It is part of a roadmap on innovative forest technologies in the Asia-Pacific region developed by FAO and CIFOR, lead center of the CGIAR research programme on Forests, Trees and Agroforestry (FTA).

According to FAO's Third Asia-Pacific Forest Sector Outlook Study (2019), the uptake and scaling-up of innovative forest technologies in the Asia-Pacific region has been slow and uneven. Young people have a key role to play in amending this condition. As technology enthusiasts and forest managers of the future, they are the individuals and cohorts to take leadership and generate momentum through collaboration and social media, transform rigid institutions from within, and participate in the uptake and upscaling of innovative technologies in the forest sector of the region.

This collection of papers illustrates, in various contexts, the potential of innovative technologies to advance sustainable forestry and sustainable forest management. It illustrates how technologies, both new and repurposed, can improve and facilitate monitoring and reporting; strengthen citizen engagement in forest monitoring and management; and support the optimization of processes and products for sustainable forestry and sustainable forest management.

The CGIAR Research Program on Forests, Trees and Agroforestry (FTA) is the world's largest research for development program to enhance the role of forests, trees and agroforestry in sustainable development and food security and to address climate change. CIFOR leads FTA in partnership with Bioversity International, CATIE, CIRAD, ICRAF, INBAR and TBI.

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