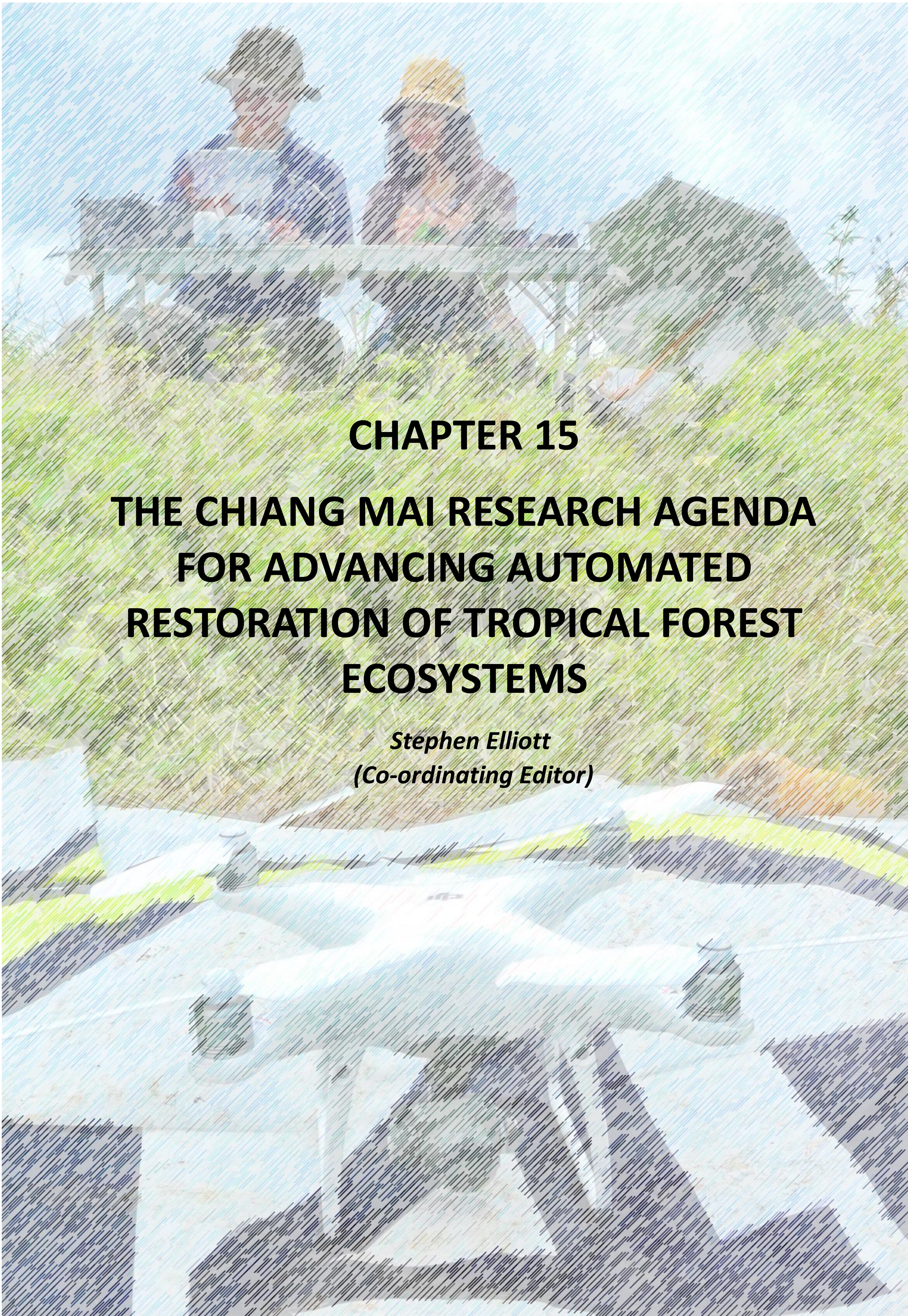

CHAPTER 15

THE CHIANG MAI RESEARCH AGENDA FOR ADVANCING AUTOMATED RESTORATION OF TROPICAL FOREST ECOSYSTEMS

Stephen Elliott
(Co-ordinating Editor)

Figure 15.1 – Dawn Frame leads a brainstorming session on automated seed-collection technologies during the first day of the workshop.

Figure 15.2 – Workshop participants vote to prioritize research topics for the advancement of automated forest restoration on the last day of the workshop.

Chapter 15

INTRODUCTION

Stephen Elliott

Two of the most important objectives of the workshop: "Automated Forest Restoration (AFR): Could Robots Revive Rainforests?" were:

1. to design research programs to improve technologies for AFR, leading to development of prototype auto-restoration systems for testing and
2. to facilitate collaboration among technologists and restoration ecologists and the formation of interdisciplinary research teams

Therefore, the main output was an agenda to guide research on AFR of tropical forest ecosystems. The workshop comprised 5 brainstorming sessions: 1) auto-seed-collection, 2) auto-seed-delivery, 3) auto-weed-control, 4) auto-monitoring (plants and animals) and 5) legal and regulatory issues. Expert speakers presented keynote topic reviews followed by discussion sessions which generated hundreds of research ideas. Screening, during plenary sessions, established general support for 95 of them. Finally, participants voted on those research ideas, which they considered most likely to advance the AFR concept – "*developing technologies that perform forest ecosystem restoration tasks on remote sites at low cost, ultimately leading to integrated, autonomous systems that minimize labour inputs to achieve restoration goals".* Thirty-nine participants each had 5 votes. The results, in declining order of support, were 1) seed bombs and pellets for automated tree establishment (41 votes[1]), 2) allelopathic herbicides for auto-weed-control (18), 3) improve drone tech (16), 4) AI for auto-tree-species recognition (13), 5) databases for species selection & restoration management (12), 6) technologies for auto-wildlife monitoring (9) and 7) data capture & indices for auto-monitoring restoration (7). These priorities were mostly re-confirmed in 2021 during an online reunion discussion with workshop participants and other AFR researchers. Only "3) improve drone tech" was lowered in priority (to 7th), since participants felt that since 2015, drone tech applicable to AFR needs, had advanced considerably. Participants in the 2021 discussion group also emphasized the need for more data-sharing among AFR researchers, funding mechanisms to support AFR research and a life-cycle approach for dealing with the e-waste that AFR might generate. **For graduate students looking for thesis-project ideas, please consider the following topics, since their need is supported by a broad spectrum of experts in the field.**

[1] Some participants voted for more than one subtropic under this heading

1. SEED BOMBS AND PELLETS FOR AUTOMATED TREE ESTABLISHMENT

Compiled by Stephen Elliott & Irina Fedorenko

RATIONAL

This topic achieved, by far, the strongest consensus at the workshop, which was reconfirmed during the reunion meeting of workshop participants, Feb 2021. It covers the need to design effective seed-containing projectiles that can be dropped or propelled from UAVs, to replace tree-planting. Aerial seeding is problematic, since dropped seeds are heavily predated and the tiny germinants are highly vulnerable to weed competition and environmental stress. Conversion of seeds to established trees is usually very low (which is also true of the natural seed rain). Therefore, seed-projectile development for AFR should aim to repel seed predators, promote germination and provide ideal conditions for seedling establishment and growth. Debate at the workshop focused on which projectile type was most suitable for drone-seeding, for various site conditions: seed bombs (seed-containing bio-degradable capsules) or conventional seed pellets (seeds encrusted or coated with various supportive or protective materials). Subtopics included testing pellet base-materials (e.g., bentonite, biochar, forest soil etc.) and addition of substances with specific functions (e.g., seed-predator repellents, fertilizers, hydrogel, fungal associates etc.). Participants also recommended comparing the relative merits of propelling projectiles into the soil by compressed air (or other propellant) or relying on the passive force of gravity. In Chapter 8 of this volume PEDRINI et al. reviewed options to consider when testing projectiles for forest tree seeds, calling for field testing of seed-delivery devices, growth matrices and coating materials. They state that seed-enabling technologies (SET) could help overcome some of the main factors that limit seedling recruitment during forest restoration projects (e.g., seed predation, suboptimal edaphic and microclimatic conditions, biotic/abiotic stresses and competition from surrounding plants). A drone-seeding company, DroneSeed[2] reported seedling establishment rates of up to 37%, using pH-stabilized, comp-ressed, fibre discs ("pucks") as seed projectiles, with a predator repellent (capsaicin), added nutrients, beneficial organisms and biochar (AGHAI & MANTEUFFEL-ROSS, 2020). Projectiles might be species- and context-specific. Gravity may be sufficient for some seeds, whereas propulsion might be needed for others. Different seed pre-treatments are probably required for different species (scarification, soaking etc.). However, bespoke solutions are expensive. So, research towards common projectile types,scalable across various species and site conditions, might be more impactful.

[2] www.droneseed.com/

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. To determine the effectiveness of various seed bomb/pellet base-materials and additives at establishing trees by drone-seeding.
2. To develop optimum seed-projectiles for tree seeds of different sizes, tree species of different successional status (pioneer or old-growth) and for sites at different degradation levels (since substrate hardness increases with increasing degradation).
3. To determine the cost-effectiveness of propelling or dropping seeds for drone-seeding.

Methodology

A wide range of seed bomb/pellet types of various designs and compositions, and various seed-pretreatments could be tested by direct seeding (by hand). The most cost-effective designs/compositions could then be tested by drone-seeding, comparing gravity vs propulsion, taking into account the additional effects of impact force, when the projectiles hit the ground. Experiments would be simple controlled replicated plots, testing the cost-effectiveness of various species-treatment-propulsion combinations. During direct-seeding experiments, the fate of individual seeds could be followed by immobilizing them in open tubes, so initial germination and seedling survival could be compared among species/treatments. Following the fate of individual drone-dropped seeds is more difficult, so measurements of tree establishment (stocking density) and crown cover (both of which can be detected by drone-mounted cameras) would be done, once trees grew taller than 1 m, compared with non-seeded control plots (natural regeneration). Cost-benefit comparisons among all combinations should also be performed.

Expected Outputs

1. Most cost-effective combinations of seed pre-treatment, projectile design/ composition for drone-seeding, for a wide range of tree species, previously proven effective for forest restoration.
2. Variations of 1) that are suitable for sites at different stages of degradation.
3. Recommendations for design of drone-mounted seed-delivery systems, based on the size/shape of the projectiles and whether propulsion or gravity turns out to be the more effective delivery force.

2. ALLELOPATHIC HERBICIDES FOR AUTO-WEED-CONTROL

Compiled by Bruce Auld and Suphannika Intanon

RATIONAL

Development of safe, effective weed control methods, to replace the common use of the herbicide, glyphosate, in forest restoration projects, was the second most important research topic, identified at the 2015 workshop; unanimously confirmed (with slight modification) by the 2021 discussion group. This topic is complementary to the proposal to replace tree-planting with drone-seeding, since germinating seedlings are far more vulnerable to weed competition than are planted trees. The use of conventional herbicides in forest restoration has several drawbacks, including non-target damage to desired tree species, drift to distant areas, high costs, impacts on human health and environmental contamination. The alternative, most favoured by workshop participants, was to exploit the allelopathic properties of plants that naturally colonize deforested sites, particularly pioneer tree species.

Allelopathy refers to beneficial or harmful effects of one plant on another via biochemicals, known as allelochemicals, transferred by root exudation, leaching, volatilization and/or decomposition. Allelopathic plants, or the allelochemicals derived from them, may be useful for the development of auto-weeding protocols, for both pre- or post-emergence weed control. In Chapter 9, AULD stressed the need for allelopathic herbicides to be species-specific (i.e., non-harmful to planted trees), whereas in Chapter 10, INTANON & SANGSUPAN proposed research to identify the source and target species of allelochemicals, evaluate their effectiveness in the field, and determine optimal timing, rates and methods of application. CHENG & CHENG (2015) caution that allelochemicals may be modified substantially by the extraction methods used. Moreover, allelochemicals used as herbicides should be subject to the same lengthy and rigorous health and safely assessments as conventional herbicides are. Direct use of allelopathic plant materials as plant amendments, to suppress weeds in forest restoration, may also be worthy of investigation. However, such materials are typically bulky and their application is labour-intensive. Consequently, they may not be suitable for aerial application by drones. Workshop delegates suggested that a more promising area for research may be to concentrate on the selection of desired tree species (or varieties) with elevated inhibitory allelopathic effects on herbaceous weeds; the development of methods to extract and identify such allelochemicals for testing as novel herbicides.

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. To identify allelopathic characteristics in tree species, available for forest restoration plantings.
2. To investigate possible breeding strategies to increase allelochemical concentrations and competitive ability within selected tree species
3. To identify allelochemicals in desired tree species and test them for pre- and/or postemergence weed control.

Methodology

Survey deforested areas for signs of allelopathy among colonizing tree species (e.g., see Fig. 10.2). Apply water-extracts from the leaves of such allelopathic trees to target weeds in replicated plots. Compare survival and growth of weeds in treated and non-treated control plots. Make a photographic record of plots. If chlorosis appears, compare chlorophyll content of treated and non-treated plants.

Extract allelochemicals using various solvents. Purify extracts and identify allelochemicals by chromatography-mass spectrometry. Perform bioassays to detect inhibitory effects of extracts, or their fractions, on seed germination and growth of a wide range of weed species, common on forest restoration sites. Test surfactants or biosurfactants (active compounds that are produced at the microbial cell surface or excreted, and reduce surface and interfacial tension) as aids for postemergence weed control.

Replicate such experiments using extracts from different tree species, provenances and individuals. Perform field experiments to test the effects of planting the most highly allelopathic trees on weed cover. Investigate genetic control of allelochemical biosynthesis and the potential to enhance it through breeding programs.

Expected Outputs

1. Identification of desired trees with allelopathic qualities and competitive advantages over other vegetation.
2. Identification of allelochemicals as novel herbicides that could be applied by drone based, smart-spraying systems for automated forest restoration.

3. AI FOR AUTO-TREE-SPECIES RECOGNITION

Compiled by Carol Garzon-Lopez

RATIONAL

Use of artificial intelligence (AI) for plant-species identification has great potential to advance AFR and empower communities to become involved in forest restoration. Delegates at the 2015 workshop ranked this topic as third highest priority; a position unanimously reconfirmed during the 2021 online workshop. Advances in automated species-recognition have arisen from the development of AI algorithms and open-source software tools (e.g., GRASS GIS, R, Python), combined with newly available UAV-borne sensors (infrared, LiDAR, multispectral, hyper-spectral etc.), capable of collecting large amounts of data on species-specific characteristics. Such datasets can form the basis of robust AI systems for automated species-classification. However, identifying tree species in tropical forests remains challenging, due to the very high species richness of such forests. Furthermore, difficult and variable environmental conditions in tropical zones can affect both data collection and its analysis.

In Chapter 3 of this volume, FRAME and GARZON-LOPEZ state that automated species identification and monitoring could have a wide range of applications in forest restoration projects, but that the types of sensors selected for such tasks should be carefully matched with both the phase of restoration and the objective of data collection. At the start of restoration projects, surveys of the target (or reference) ecosystem are required, to accurately determine its species composition (to establish restoration goals) and to locate potential seed trees (to generate planting stock). This might be achieved by combining data from several sensors (e.g., infrared, multispectral, LiDAR, hyperspectral) and developing more reliable AI algorithms.

Further research is needed to explore how gradients of environmental or land-use intensity affect the accuracy of the AI algorithms. Another consideration is the need develop species-classification systems, which are widely transferable to locations other than where they were first developed, and which are applicable at a range of different scales. A greater understanding of sources of error and how to eliminate or compensate for them is also needed, if automated species identification is to play a substantial role in the advancement of AFR (FASSNACHT et al. 2016).

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. To determine which species can be classified using AI using data from a combination of UAV-borne sensors.
2. To evaluate the minimum resolution and quantity of data (e.g., RGB vs. hyperspectral) required to accurately identify species of interest for restoration, using a range of AI algorithms.
3. To assess the transferability of classification setups to forest sites at various levels of disturbance and with trees of various species and age classes.

Methodology

Select large primary or secondary forest patches, with adequate sample sizes of each of the species of interest. Perform drone flights to capture data, if possible, using multiple types of sensors. Repeat the data collection at various resolution levels, to capture images of the trees at all phenophases (flowering, fruiting, leaf flush/fall). Perform parallel ground surveys, using GPS, to locate target trees and verify their identification. Develop a range of different AI algorithms for species-classification analyses (using free open-source software tools, such as GRASS GIS, R, Python etc.), and use the ground survey data to evaluate their accuracy. Repeat for other forest patches with varying degrees of degradation and restoration, using the training data from initial patches, to test the transferability of data setup protocols across disturbance gradients and for various age classes.

Expected Outputs

1. Guidelines for AI tree-species identification setup, including optimal sensors (and their settings), AI approach and resolution.
2. A protocol for effective UAV-borne data-collection specifying the optimal season, age-class, and degree of disturbance, for maximum classification accuracy.
3. A framework for the application of these research protocols to other ecosystems and restoration projects, using free, open-source software.

4. DATABASES FOR SPECIES SELECTION & RESTORATION MANAGEMENT

Compiled by Gunter A. Fischer, Lisa Ong & Stephen Elliott

RATIONAL

Forest restoration planning is heavily data-dependent. Delegates at the 2015 workshop ranked databases as a moderate priority to support restoration planning. Although some progress has been achieved since 2015, participants in the 2021 review retained databases as a priority (ranked 4th), since data on more tree species are required, as well as distribution maps and image libraries, to support training of AI species-identification systems. Several chapters in this book highlight the need for expansive databases, to support pre-restoration site surveys (Chapters 3, FRAME & GARZON-LOPEZ & 4, MIRANDA et al.), post-restoration monitoring (Chapter 12, CHISHOLM & SWINFIELD) and particularly species selection. Data on species distribution (maps), phenology (particularly fruiting), seed-dispersal mechanisms, seedling biology and propagation protocols, combined with an integrated species-identification tool, could all contribute to better-informed species choices. A functional-trait-based approach, combining ecological data with species- perform-ance indices, under various environmental conditions, was recommended in Chapter 6 (BECKMAN & TIANSAWAT). Recent advances in online database systems (e.g., GBIF[3], iNaturalist[4,] PlantSnap (Chapter 11, BONNET & FRAME) etc. and initiatives, such as BGCI's Global Tree Assessment[5] have increased knowledge of tree-species distributions, threat levels and have contributed to automated plant identification. Furthermore, advances in species-distribution modelling are enabling species reintroductions and translocations for restoration to be planned for various climate-change scenarios, e.g., Bioversity's D4R tool[6]. However, more efforts are needed to compile ecological and restoration information in detailed, user-friendly, species profiles. Attempts to link scattered databases of restoration-relevant information (e.g., Global Restore Project[7]) have yet to have an impact. Furthermore, restoration-relevant data, such as interspecific interactions (AUSSENAC et al., 2018), animal seed-dispersal mechanisms & distances and landscape connectivity (TIMÓTEO et al., 2018) are currently found only in academic publications. What is needed is a user-friendly expert-system, which integrates data from multiple sources to provide the best possible data-driven advice to restoration practitioners.

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[3] www.gbif.org/what-is-gbif; [4] www.inaturalist.org/
[5] www.bgci.org/our-work/projects-and-case-studies/global-tree-assessment/; [6] www.diversityforrestoration.org/tool.php
[6] www.globalrestoreproject.com/

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. Develop API's (application programming interfaces), in collaboration with existing online databases and tools, to integrate existing data and extend species coverage and functionality, culminating in an online expert-system for forest restoration planning, including species-site matching and restoration-management recommendations.
2. Add image libraries to such systems, particularly containing images of identified tree crowns from above, to provide training images for AI tree identification tools.
3. Enable restoration practitioners to feed data from their projects into the system – so it can "learn" from successes and failures.
4. Develop an algorithm, capable of automatically extracting restoration-relevant information from academic publications and adding it to the expert system.

Methodology

Perform a data-needs assessment and gap-analysis with restoration practitioners in collaboration with organizations developing databases and online tools. Develop software and algorithms, to design the API's and expert system. Engage with open-source software-development communities, to make the system freely available online.

Expected Outputs

1. An expert system, which provides guidance to restoration practitioners on all aspects of restoration implementation, suited to site conditions, from planning, species selection, seed collection, planting stock propagation, maintenance and monitoring.
2. An expert system that gradually increases the effectiveness of output advice by "learning" from performance data, input by project managers, and from information autonomously integrated from online academic publications.
3. An image library (particularly of tree crowns of known species from above) for training AI tree-species-identification systems.

5. TECHNOLOGIES FOR AUTO-WILDLIFE MONITORING

Compiled by George Gale and Antoinette Van de Water

RATIONAL

Since biodiversity recovery is a primary aim of forest ecosystem restoration, biodiversity monitoring is essential to determine restoration outcomes. Although technologies for auto-monitoring plant diversity recovery are advancing relatively rapidly (see priority #3), technologies for auto-monitoring recovery of bird and mammal diversity (particularly of crucially important seed-dispersing animals (Chapter 13, GALE & BUMRUNGSRI)) have lagged behind. This topic was ranked 5th in priority at the 2015 workshop, confirmed with modification during the 2021 review.

Different groups of target species require different kinds of hardware and software for auto-sampling and field data collection. In Chapter 13, we focused on available hardware and software for automating surveys of birds and insectivorous bats. However, the 2015 workshop delegates voted to prioritize research on drone-mounted thermal cameras for wildlife monitoring, whilst participants in the 2021 review reprioritized using UAVs as 'data mules' to retrieve data from camera traps and microphones from remote locations, and the potential of using such images or sounds in citizens'-science projects.

While thermal infrared sensors on drones are getting better at detecting and identifying arboreal mammals—even exceeding the detection rates of ground-based human observers (ZHANG et al. 2020)—their use comes with several technical challenges. These include thermal contrast problems, due to heat from the ground, absorption and emission of thermal infrared radiation by the atmosphere, obscuration by vegetation, and optimizing the flying height of drones for optimal balance between covering a large area and being able to accurately image and identify animals of interest (BURKE et al. 2019). Although sensors and machine learning will undoubtedly improve, drone-based thermal imaging is rarely successful where vegetation cover is dense (KARP, 2020). Under such conditions, conventional camera traps or acoustic monitoring are more suitable (BEAVER et al., 2020). In dense tropical forests, where monitoring in person can be problematic, acoustic monitoring provides a non-invasive, cost-effective solution. However, calls of some species are inaudible to the human ears, such as ultrasonic bat calls (see Chapter 13) or infrasonic elephant calls. Novel compression methods, to monitor elephant sounds makes automatic data extraction possible, and can be adapted to acoustic monitoring of a range of other species (BJORCK et al., 2019).

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. To field-test the bias and precision of data, collected by drone-mounted thermal cameras, for surveying seed-dispersing terrestrial mammals, compared to camera traps and microphones.
2. To compare effectiveness of imaging and acoustic technologies for auto-monitoring wildlife.
3. To develop an automated system to monitor wildlife recovery by integrating imaging and acoustic technologies with the use of UAVs as 'data-mules'.
4. To improve techniques to analyse imaging and acoustic data for auto-recognition of wildlife species, including a 'citizens'-science' approach to collect and analyse data (i.e., classify images and bird song recordings).

Methodology

This research could combine different technologies, or focus on a technology of choice to monitor wildlife recovery in forest restoration sites. Firstly, continuous surveys by drones with thermal cameras could be conducted at different times of the day (e.g., morning, evening, night) and of the year (e.g., dry vs wet season, hot vs cold days, cloudy vs sunny days) to compare the influence of temperature, clouds, and vegetation cover on wildlife detection. In addition, camera traps with Wi-Fi signals, ideally powered by solar cells, can be set up in a restoration area focusing on monitoring civets, deer or other seed-dispersing terrestrial mammals. Experiments with drones as data mules can then be conducted to test remote data collection from camera traps and/or microphones. The collected photos, videos or sound clips can be uploaded to data management software and AI systems developed for auto-identification of species. Such systems could be tested by a citizens'-science approach, using large numbers of people to compare and classify images and recording, effectively training AI systems under development.

Expected Outputs

1. Understanding of the estimated frequency of drone surveys with thermal cameras, and needs for additional technologies to reach an optimum automated methodology to obtain sufficient samples.
2. Ultimately, drone-based systems of sufficient reliability to replace or complement camera trap data.

6. Data Capture & Indices for Auto-Monitoring Restoration

Compiled by Carol Garzon-Lopez and Gunter Fischer

RATIONAL

The 2015-workshop delegates ranked this topic as medium priority. Although this field has advanced since 2015, participants in the 2021 online review voted unanimously to retain it on the priority list, with modifications: future research should focus on lidar technologies and phenocams (time-lapse photography from static cameras) for long-term fine-scale restoration monitoring.

Aerial imagery and lidar data, collected by multiple sensors, mounted on various platforms, offer new possibilities for restoration-site assessments and post-restoration monitoring, compared with non-restored control sites and old-growth reference forest. Various integrated technology combinations should be tested and calibrated, to achieve high standards of data accuracy and precision, cost-effectiveness and seamless interoperability. The design and development of integrated auto-monitoring systems will depend on how well each combination of camera/LIDAR and platform meets the monitoring requirements of each restoration phase – from small saplings to mature trees. During the 2015 workshop, discussion centered around the application of aerial surveys to inform pre-restoration project planning, and post-restoration monitor of tree performance, forest canopy expansion and forest structure development. Since 2015, small, drone-mountable lidar and multi-spectral sensors have become available (but remain very expensive), enabling accurate assessments of tree size and growth, biomass (including carbon accumulation) and forest structure at relatively low cost. Collaboration with new satellite- and machine-learning-based restoration monitoring enterprises, such as Pachama (pachama.com/) and Restor (restor.eco) could be explored, to identify gaps in data needs and possible applications for the use of drone-based monitoring to fill them. Combinations of air-borne data with time-lapse images (captured by phenocams) could be explored, to enable inclusion of fine-scale monitoring of tree phenology and the performance of small seedlings and saplings into indices of restoration progress.

In Chapter 5, Chisholm & Swinfield highlighted the need for selection of accurate restoration indicators, to guide the application of useful platforms, sensors and analyses. Systems development is still needed, particularly for diverse tropical forests, where monitoring across multiple restoration phases remains challenging.

SUGGESTED RESEARCH PLAN OUTLINE

Objectives

1. To compare performance of satellite and drone-based imagery and lidar for capturing data on tree growth, forest biomass (carbon) and structure both pre- and post-restoration implementation, compared with non-restored control sites and old-growth reference forest remnants (target).
2. To identify the best platform-sensor-indicator combination for each indicator for monitoring each restoration phase.
3. To develop protocols to integrate monitoring data and make them widely available through free, open-source, data libraries, for transparent, transferable capacity-building.

Methodology

Use time-series satellite and/or drone imagery to determine forest-degradation history and causes, across the selected restoration landscape, and to map relevant landscape features (e.g., water bodies, human settlements, topography, etc.) in order to select suitable locations for restoration interventions and control plots. Establish long-term restoration plots on sites covering a gradient of disturbance levels, as well as control plots (no-intervention) and reference forest plots (target). In each plot, perform ground surveys and install phenocams. Record GPS locations and tag each tree and measure their height and diameter at regular time intervals (see forestgeo.si.edu for protocols). Calculate rates of survival, growth and carbon capture (using established allometric equations). Use drone-borne imagery, lidar to collect data from each plot and process them to construct 3D forest models. Correlate measurements of tree height, growth and survival from the 3D models with ground-based field data. Compare strength of such correlations among various platform-sensor-indicator combinations for sites at various stages of restoration/ degradation. Test use of phenocams images to monitor performance of saplings.

Expected Outputs

1. Optimal technology combinations for data collection and indices for auto-monitoring restoration progress
2. Protocols for data collection and analyses made freely available online for each stage of degradation/restoration.

7. Improve Drone Tech

Compiled by Lot Amoros and Irina Fedorenko

In 2015, drone technologies were at an early stage of development—consumer drones had only just arrived in stores. Most of their shortcomings for AFR purposes were detailed in Chapter 2 (Tiansawat & Elliott): short battery life, limited range and lifting ability, lack of object-avoidance and susceptibility to wind and rain. Since most AFR tasks, were to be performed by drones, research to improve drone technologies was ranked highly by the 2015 workshop participants: 3rd order of priority. Extending battery life and reliable object-avoidance systems, when flying close to or below forest canopies, were considered crucial.

However, by 2021, drone technologies had improved considerably. Consequently, participants in the online review relegated research on drone technologies to lowest position (7th) on the priority list.

Most consumer drones now come with effective auto-object-avoidance systems and both battery life and connectivity range (between drones and controllers) have improved. This has greatly increased the capability of drones to perform AFR tasks. However, since flight times of most consumer drones are still limited to around 30 minutes, it is still necessary to carry into the field multiple battery packs and/or a charging system. However, doing so enables coverage of several hectares during a single day's work. On-board RBG cameras have increased in resolution and image quality, enabling structure-from-motion (SfM) programs to be used to construct both detailed orthorectified site maps and 3D forest models, without the need for lidar. Multispectral cameras and lidar sensors are now beginning to become available on consumer drones, although such drones are very expensive. Lifting power has also increased up to 25 kg, although flight times when carrying such heavy loads are reduced to around 15 mins, and, again, commercially available heavy-lifting drones are very expensive.

Focus has shifted from technical limitations to regulatory ones (see Chapter 14 (Tiansawat et el.)—such as limits of 25 kg for drones with their payloads in most countries. It is important that regulators understand that AFR drones fly over unpopulated areas, at elevations well below those used by air traffic, so issues of invasion of privacy and encroachment into aircraft flight paths rarely apply. Furthermore, AFR drone flights potentially bring about immeasurable benefits to the environment and downstream communities. Consequently, there are strong arguments to exempt AFR drones from some of the unnecessarily restrictive regulations, both current and proposed.

Technical development of drones for aerial seeding has mostly been carried out by a few companies, which market drone-seeding services to large reforestation projects commercially. Consequently, such technologies (e.g., pneumatic propulsion and seed “brick” release) are not openly available for widespread use and independent testing, since they are the intellectual property of the companies that developed them. Only the seed-spreading technology of Dronecoria is open-source (dronecoria.org/ en/main/). Wider implementation of AFR technologies, therefore depends on balancing commercial interests with community needs. However, contracting specialist companies to perform drone-seeding for AFR, with existing technologies is an option that circumvents the need for further technological research at the project level. In addition to Dronecoria, referenced above, the following companies now offer drone-seeding to forest restoration projects commercially: Dendra Systems (dendra.io/), DroneSeed (droneseed.com/), Airseed (airseedtech.com/), CO2Revolution (co2revolution.es/) and Flash Forest (co2revolution.es/). The advantages of working with such companies is that they already have experienced teams, working on the basis of previous field tests, to achieve the desired sowing density, precision, etc.

Ideas for further research on drone technologies and use, specifically for AFR, under the harsh conditions of tropical zones include:

1. Further development of fuel cell technology, to power drones for several hours – lighter, more powerful and affordable units than those currently available.
2. Development of solar-powered batteries to charge magnetic-induction pads for autonomous and continuous drone-battery charging, under all weather conditions.
3. Ruggedization of drone technology, enabling continuous long-term use in all weathers, with minimal maintenance.
4. Research on the complex logistical, socio-economic and cultural issues related to drone usage in rural areas and their capability to accelerate land-use changes over wide areas.

REFERENCES

AGHAI, M. & T. MANTEUFFEL-ROSS, 2020. Enhancing direct-seeding efforts with unmanned aerial vehicle (UAV) "swarms" and seed technology. Tree Planters' Notes 63(2):32-48.

AUSSENAC, R., Y. BERGERON, D. GRAVEL & I. DROBYSHEV, 2019. Interactions among trees: A key element in the stabilizing effect of species diversity on forest growth. Func. Ecol. 33(2): 360-367.

BEAVER, J.T., R.W. BALDWIN, M. MESSINGER, C. NEWBOLT, S. DITCHKOFF & M.R. SILMAN, 2020. Evaluating the use of drones equipped with thermal sensors as an effective method for estimating wildlife. Wildlife Soc. Bull. 44(2):434–443. https://doi.org/10.1002/wsb.1090

BJORCK, J., B.H. RAPPAZZO, D, CHEN, R. BERNSTEIN, P. WREGE & C.P. GOMES, 2019. Automatic detection and compression for passive acoustic monitoring of the african forest elephant. Proc. AAAI Conf. A.I. 33(1):476-484. https://doi.org/10.1609/aaai.v33i01.3301476

BURKE, C., M. RASHMAN, S. WICH, A. SYMONS, C. THERON & S. LONGMORE, 2019. Optimizing observing strategies for monitoring animals using drone-mounted thermal infrared cameras. Int, J. Remote Sens. 40(2):439-467.

CHENG F. & Z. CHENG, 2015. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. Front. Plant Sci. 6: 1020. Doi: 10.3389/fpls.2015.01020

FASSNACHT, F.E., H. LATIFI, K. STEREŃCZAK, A. MODZELEWSKA, M. LEFSKY, L. T. WASER, C. STRAUB & A. GHOSH, 2016. Review of studies on tree-species classification from remotely sensed data, Remote Sens. Env., 186: 64-87. doi.org/10.1016/j.rse.2016.08.013.

KARP, D., 2020. Detecting small and cryptic animals by combining thermography and a wildlife detection dog. Sci. Reports, 10(1), 5220. https://doi.org/10.1038/s41598-020-61594-y

TIMÓTEO, S., M. CORREIA, S. RODRÍGUEZ-ECHEVERRÍA, H. FREITAS & R. HELENO, 2018. Multilayer networks reveal the spatial structure of seed-dispersal interactions across the Great Rift landscapes. Nature Commun. 9(1):1-11.

ZHANG, H., C. WANG, S. T. TURVEY, Z. SUN, Z. TAN, Q. YANG, W. LONG, X. WU & D. YANG, 2020. Thermal infrared imaging from drones can detect individuals and nocturnal behaviour of the world's rarest primate. Glob. Ecol. Conserv. e01101.2351-9894, doi.org/10.1016/j.gecco.2020.e01101.