AUTOMATED Forest Restoration

Editors:

Stephen Elliott
George Gale
Mark Robertson

FOREST
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THANKS TO OUR SPONSORS …

… AND TO ALL PARTICIPANTS!

Cover – Photos from the workshop's field day (by Stephen Elliott)

AUTOMATED FOREST RESTORATION: COULD ROBOTS REVIVE RAIN FORESTS?

PROCEEDINGS OF A BRAIN-STORMING WORKSHOP
CHIANG MAI UNIVERSITY, THAILAND, 2015

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DEDICATION – DAVID LAMB

Dr. David Lamb, who penned the foreword on the next page, sadly passed away in March 2019, before this book could be published. We dedicate this volume to his memory. A pioneer of forest restoration science in the Asia-Pacific Region and one of FORRU-CMU's most ardent supporters, David was a Professor at the University of Queensland. He was an inspiring teacher, prodigious researcher and supportive student advisor, working on forest projects from Australia to Papua New Guinea, Vietnam and here in Thailand. He ran several workshops with us and helped raise funds for our work on mapping land use in the Mae Sa Valley and its subsequent presentation at an IUFRO conference in Seoul. He also supported our involvement in IUCN's Landscapes and Livelihoods (LLS) model site at Doi Mae Salong. His many books and papers have become essential reading for both students and professionals. He was a very familiar face at conferences and workshops that helped to shape such concepts as Forest Landscape Restoration, Assisted Natural Regeneration and Ecological Services. The forests of Asia-Pacific have lost one of their most fervent champions. Conferences and workshops will seem a little emptier without his insightful presentations and wise chairmanship. But his prolific publications are a lasting legacy that will continue to inspire young foresters for many generations to come.

Stephen Elliott

FOREWORD

The amount of degraded land, now present across the world, continues to increase, meaning that the task of restoration also grows. This will require more information about the basic ecology of these ecosystems, as well as a better understanding of how restoration may be done, in ways that improve the livelihoods of people living in these degraded landscapes. But it will probably also require a change in the way we tackle the job. Costs will have to be reduced, to maximize the use of limited financial resources, and methods will have to be devised, to deal with severely degraded sites and those that are difficult to access.

In recent years, several new tools have become available that should improve our ability to undertake restoration. These include satellite imagery and global positioning systems (GPS). Both technologies should be very useful in defining areas to be treated and helping to plan how treatments will be undertaken. Useful versions of each of these are now accessible to anyone with a smart phone. A third potentially useful new technology is the development of cheap unmanned aerial vehicles (UAVs) or drones, able to carry payloads, such as digital cameras, and to be guided by relatively simple technology. These are rapidly evolving in size and capability. The price of drones is also dropping, making them more readily available to even financially-stretched field workers.

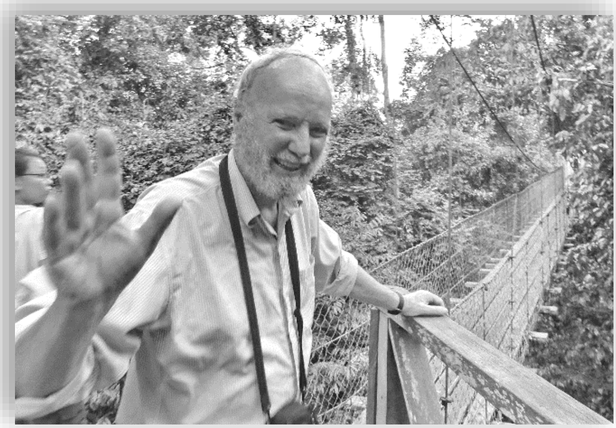
But the question is how can this technology be used? We know drones can carry cameras and perform low-altitude photography. This means we can now obtain up-to-date and high-quality imagery of field sites and no longer have to depend on satellites imagery that may be out of date. However, it is also becoming clear that there are, potentially, a host of other opportunities from drones that are starting to emerge. For example, they may be used to help identify seed sources in highly fragmented landscapes, where it can be difficult to determine where trees of particular species still remain. They may also have a role in distributing seeds (or even seedlings) to isolated sites that are difficult to access. Might they even have a role in collecting seed?

New ideas often seem radical, when they are first introduced, and are commonly dismissed as being unworkable (e.g., "That won't work because ...."). But it is also often the case that, several years later, the advantages and utility of those ideas seem obvious to everyone (e.g., "I always knew this would work ...."). I expect this to be the case concerning the utility of aerial drones for forest restoration. In fact, I saw the first signs of this when a colleague of mine tentatively offered a poster some years ago at an international tropical biology conference, in which he described what he thought might be some of the ways in which drones might be used in future forest restoration. I suspect he thought he was being somewhat adventurous and perhaps even a little outlandish with some of his suggestions. But the poster was aimed at provoking discussion. He was therefore rather taken aback when several people come up to his poster and said that they were already working on, or even had implemented, some of the ideas presented. He was not being outlandish at all! There were others out there, already thinking along similar lines.

This book reports on some of the early work being carried out by some of these "others". It explores how this new technology might be utilized in undertaking forest restoration and is the outcome of a workshop, held at the University of Chiang Mai in Thailand in 2015. The overall objective of the workshop was to consider how drones might be used to automate the process of restoration and accelerate the rate at which the large areas of degraded land can be tackled. The workshop brought together researchers from a variety of backgrounds and biomes. The scope of the contributions is wide, ranging from the use of drones to locate seed sources, through to developing new methods of weed control and seed distribution. It is clear that we are still in an early development phase, and much remains to be done before the use of drones becomes routine. But it is also clear that the potential use of drones, to undertake forest restoration, has captured the attention and imagination of many people in different parts of the world and that we can reasonably expect considerable and rapid advances in the next few years.

It would be remiss of me not to mention the role of the Forest Restoration Research Unit of the University of Chiang Mai (FORRU-CMU) in organizing this workshop. FORRU-CMU has long been amongst the leaders in developing methods to restore tropical forests and is to be congratulated for organizing this meeting and bringing together such a wonderful assembly of authors. I heartily commend this book to all those interested in forest restoration.

David Lamb
Brisbane, Australia

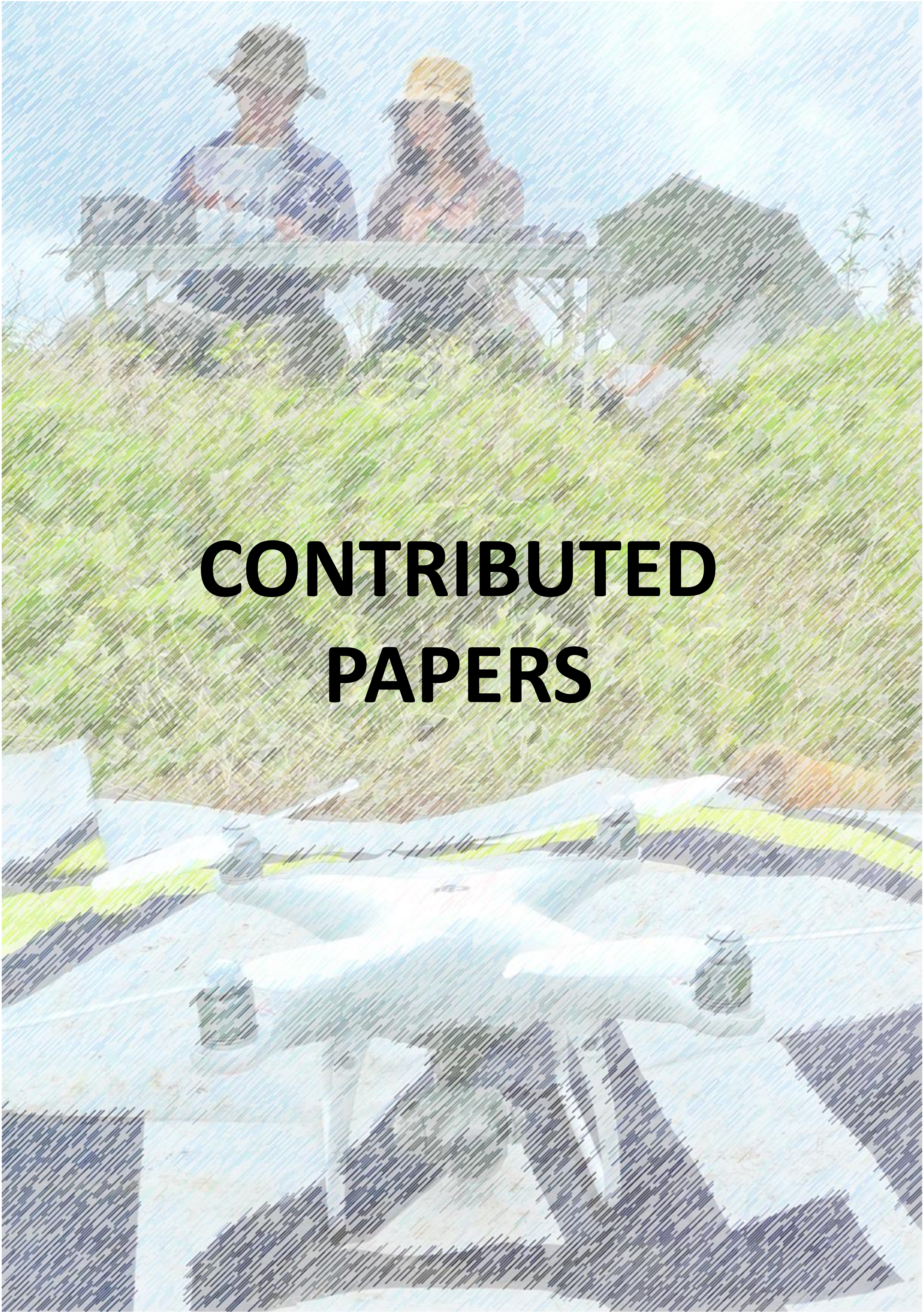


Canopy walkway, Sabah, at the Symposium for Rainforest Rehabilitation & Restoration, July 2011 (photo S. Elliott).

PREFACE

The seed of "automated forest restoration" (AFR) germinated in June 2009. Having spent an arduous field-day with our German project partners, collecting carbon samples in FORRU's restoration plots, we retreated to the Grandview Hotel for dinner (coincidently where we would run the AFR workshop 6 years later). Conversation turned to how labour-intensive forest restoration is and how nice it would be if robots could do some of the work. As beer flowed, we joked about fantastic flying machines to collect seeds, plant trees and care for them. That night, I Googled some of the technologies that would be needed; it turned out that the concept was far from a joke. Although consumer drones had yet to arrive in stores, DIY drones were already being adapted to drop seeds. We approached Dr Annop Ruangwiset (King Mongkut's University of Technology Thonburi), and in April 2014, he tested a seed-dropping drone. Seeds were successfully dropped that day, but the drone crashed into a tree. Clearly much more research was needed, if AFR was to become a reality. However, meetings with potential funders and collaborators often ended with raised eyebrows and, on one occasion, being accused of having "watched too much Star Trek". However, talking with David Lamb one night, on the veranda of a bungalow in Sabah's Maliau Basin National Park, during a workshop there, he mentioned that Australian researchers were testing drones for mine re-habilitation and encouraged us to go public with our integrated AFR concept. So, in July 2014, we presented a poster at the ATBC Conference in Cairns: "Exploring the Feasibility of Automated Forest Restoration". It generated much interest and we realized that our ideas were no longer science fiction; though it took another year to raise funds for a brain-storming workshop. Meanwhile, BioCarbon Engineering became the first company to seed a forest by drone. We recruited key speakers in a wide range of fields, from aeronautics and AI to seed technology and forest ecology—connecting experts who rarely interacted. They inspired participants to dream up research ideas, during discussion groups, on auto-seed collection, drone-seeding, auto-weeding, monitoring etc. We even ran a field day, to test drones for finding seed trees, seed dropping and spraying herbicides. The result was one of the most productive workshops I have ever participated in … and the 15 chapters of this book. Hopefully, they will inspire researchers to continue AFR's transformation from science fiction to reality, making forest ecosystem restoration more practicable and cost-effective at this time when global interest in restoration has never been greater.

Stephen Elliott
(Co-Director, FORRU-CMU)



CONTRIBUTED PAPERS

Figure 1.1 - During the workshop field day, prototypes of various technologies that might assist forest restoration tasks were demonstrated. Here a drone, developed by CMU Physics Department, prepares to drop tree seeds in simple paper seed bombs, containing seeds, forest soil and hydrogel.

Chapter 1

Forest Restoration: Concepts and the Potential for its Automation

***Stephen Elliott*[1]**

ABSTRACT

In 2014, the UN New York Climate Summit set a goal to restore forest to 350 million hectares of degraded land by 2030, to counter climate change. Conventional tree-planting with human labour is unlikely to achieve this goal, due to the inaccessibility of most sites available for restoration and limited labour availability. This paper, therefore, establishes the basic concepts of forest restoration (ecological restoration), summarizes the tasks necessary to achieve it and the potential for emerging technologies to carry them out.

Drones, with tree recognition software, could rapidly provide GPS co-ordinates of native seed trees, in natural forest, to seed collectors or they might collect seeds autonomously, using robotic arms, suction tubes or rotating brushes. Drones are already being used to carry out aerial seeding. The need is to develop rapidly biodegradable “designer seed-bombs”, which protect seeds from desiccation with hydrogels, whilst also providing them with fertilizers, growth promoters and micro-organisms to promote rapid seedling establishment. Combined with plant recognition technology, drones might also be able to spray herbicides to control weeds, whilst avoiding killing trees and accurately deliver fertilizer around establishing tree seedlings. These processes could be fully automated, by recharging drone batteries with solar-powered inductive charging pads.

Monitoring forest canopy closure is already possible with drone-mounted sensors. Advances in plant recognition software will probably enable auto-monitoring of plant species recovery soon, whilst recovery of bird or mammal communities could be recorded by remote microphones and camera traps. Data from such devices could be transmitted via the telephone network or by using drones as “data mules”. Many of the above-mentioned technologies already exist, but to develop practical auto-restoration systems, they must be improved (e.g., longer battery life), made cheaper and more rugged, to operate for long periods in tropical climates. Intensive collaboration among ecologists and technologists, will be essential to achieve viable and cost-effective auto-restoration systems.

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FOREST RESTORATION - FROM PIPEDREAM TO GLOBAL IMPERATIVE

Thirty years ago, the idea of restoring tropical forest ecosystems was regarded as the "pipedream" of a handful of ecologists. Many other ecologists dismissed the idea as unattainable, believing that the high structural complexity and biodiversity of such ecosystems could never be recovered. Some conservationists also opposed even research to develop restoration techniques, claiming that it was an unnecessary distraction from the overriding need to secure remaining primary forests within protected areas They argued that it might actually encourage deforestation, by creating a "destroy now - restore later" mentality amongst developers.

Although, tropical forests should be restored for many reasons (forest products, watershed protection and other environmental services, wildlife conservation, alleviating rural poverty etc.), it is the growing concern over global climate change, and the role that forests could play in its mitigation, that has recently propelled tropical forest restoration from an unattainable pipedream into a global necessity. One of the main reasons for this has been the development of REDD++[2]. Originally conceived as a mechanism merely to reduce the rate at which CO_2 from forest destruction entered the atmosphere, the initiative was subsequently expanded to include "enhancement of carbon stocks" (United Nations, 2007) i.e., removal of CO_2 from the atmosphere by forest expansion. This now makes forest restoration more eligible for funding, from the Green Climate Fund, national governments, carbon credit markets, the CSR programs[3] of international companies, etc. However, two important safeguards apply (United Nations, 2010, safeguards (d) and (e)). Firstly, restoration must be carried out with the "full and effective engagement of indigenous peoples and local communities", which most likely means that restored forests will have to provide local communities with the same variety of forest products and ecological services, as the original forest once did. Secondly, actions must be "consistent with the conservation of natural forests

Figure 1.2 – Ambitious restoration targets will not be achieved using stone-age techniques.

[2] Reducing Emissions from Deforestation and Forest Degradation in developing countries, including conservation, sustainable management and enhancement of carbon stocks - policies and incentives, developed under the UN Framework Convention on Climate Change (UNFCCC).

[3] Corporate Social Responsibility

and biological diversity and used to incentivize the protection and conservation of natural forests and their ecosystem services and to enhance social and environmental benefits".

Neither of these safeguards are achieved by conventional plantations of fast-growing tree species. Consequently, "ecological restoration" (acc. Lamb, 2015) must be carried out to recreate structurally complex and biodiversity-rich forests, to meet both these safeguards. Consequently, the following definition applies:

"Forest restoration is directing and accelerating ecological succession towards an indigenous target forest ecosystem of the maximum biomass, structural complexity, biodiversity and ecological functioning that are self-sustainable within prevailing climatic and soil limitations" (adapted from ELLIOTT et al., 2013), where aims include:

1. carbon sequestration (since biomass determines carbon storage);
2. biodiversity recovery (since structurally complex forests trend towards maximum equilibrium species richness) and/or
3. delivery of a diverse range of forest products (from biodiversity enhancement) and ecological services to communities.

Since the definition includes climate dependence, and climate change is unpredictable, restoration should also maximize ecosystem adaptability by:

1. maximizing species and genetic diversity and
2. facilitating gene mobility.

Restoration science advances but technologies remain pre-historic

Luckily, the science of tropical forest restoration has progressed considerably over the past 20-30 years, such that lack of knowledge and skills no longer impede its implementation. Research has greatly improved methods of site assessment and planning, tree species selection, seed collection and the propagation of native forest tree species in nurseries, tree planting and direct seeding, as well as care for planted trees in restoration sites (weeding and fertilizer application regimes etc.) and finally the monitoring of forest ecosystem recovery, from canopy closure to the return of wildlife communities (ELLIOTT et al., 2013).

Such research has enabled ecologists to develop restoration systems, capable of restoring diverse forest ecosystems to forestland at all stages of degradation (ELLIOTT et al., 2013, Chapters 3 & 5) such as:

1. protection and assisted or accelerated natural regeneration (on moderately degraded sites, where surviving natural regeneration is sufficiently dense to rapidly close canopy e.g., the ANR approach, favoured by the FAO (Shono et al., 2007);
2. planting a few selected tree species to complement natural regeneration, where it is less dense and where natural seed dispersal can recover species richness, e.g., the framework species method of Goosem & Tucker (2013);
3. planting all or nearly all species that once comprised the original forest tree community, where lack of natural seed-dispersal limits recovery of tree species richness, e.g., the maximum diversity method of Goosem & Tucker (2013) and the Miyawaki method (Miyawaki, 1993) and
4. planting nurse trees to improve the soil (e.g., legumes (Siddique et al., 2008)), on the most degraded sites, where soil degradation precludes other restoration methods.

The design, size and placement of restoration plots has also received considerable attention, particularly to provide maximum ecological benefits with minimum costs. Just restoring forest corridors – narrow strips of forest, linking existing forest remnants – can encourage seed dispersal and movement of wildlife across landscapes, thus reducing genetic isolation, whilst occupying little land and requiring minimal inputs (TUCKER & SIMONS, 2009). Restoring just small forest "nuclei", dotted across deforested landscapes, can also catalyse widespread forest recovery with minimal effort. This "applied nucleation" approach (ZAHAWI et al., 2013) encourages natural seed dispersal and seedling establishment around the nuclei perimeters, leading to their expansion and eventual coalescence.

Forest restoration methods have been developed for many different circumstances, from providing local communities with foods and materials (e.g., rainforestation farming (SCHULTE, 2002)) to rehabilitating open-cast mines (PARROTTA et al., 1997). Such pragmatic approaches have recently given rise to the relatively new discipline of "forest landscape restoration" – the study of how to integrate forest restoration sites, amidst other land uses and which types of restoration are most appropriate to maximize both ecological and economic benefits at the landscape level (REITBERGEN-MCCRAKEN et al., 2007).

Although the above-mentioned achievements have vastly improved forest restoration methodologies, over a wide range of initial conditions and ecosystem types, when it comes to implementing restoration on-the-ground, the technologies used have remained persistently prehistoric. Typical restoration projects involve large numbers of people, acting as "human mules" carrying baskets of seedlings, equipment and materials, often over long distances, across rough, steep terrain to remote restoration sites (Fig. 1.2). Weeds are slashed with machetes and planting holes dug with hoes, in much the same way as our iron-age ancestors would have done.

Lack of access is the main problem. Most flat sites, close to roads, are already occupied with agriculture and consequently they are not available for forest restoration. So, most restoration sites are remote, often on steep slopes with infertile soils. Expecting people to haul trees, materials and equipment into such sites, for tree planting and to return frequently enough, to carry out weeding, fertilizer application and monitoring, to the extent required for successful restoration, is unreasonable. Restoration work is generally low paid, temporary and seasonal and consequently, it does not generate a regular income. Theoretically, local people should be willing to do such work, in exchange for the benefits they receive, but the benefits are uncertain, far in the future or they remain largely "theoretical" or inaccessible e.g., carbon credits or payments for other environmental services. Markets that could turn such benefits into cash flows are mostly undeveloped or confusing and local villagers have little access to them or simply do not trust them. Automation of any restoration tasks would, therefore, make forest restoration, on the scale envisaged by the UN, much more feasible.

Most current restoration projects rely on tree planting as the main initial intervention. Production of high quality, disease-free tree saplings, of a diverse range of native forest tree species, by the optimum planting season, is problematic. Nurseries are expensive to build and run. Many of the tree species, useful in ecological restoration, have never been mass-propagated before. Furthermore, recruiting and training staff, capable of carrying out the research, necessary to develop cost-effective propagation methods, requires levels of expertise and management that are both rare and expensive. Growing trees in nurseries is often beset with administrative problems. Once government officials and sponsors have decided to push ahead with a restoration project, they often demand unrealistically rapid results. Informing such officials that they will have to wait 12-18 months to produce the planting stock, before high-profile tree-planting events can be staged, often kills off such projects, before they get off the ground. An obvious solution to such problems is to plant seeds, instead of tree saplings. Recent research on direct seeding suggests that for many tree species, this approach is more practical and cost-effective than conventional tree planting (TUNJAI & ELLIOTT, 2012 & TUNJAI; Table 5.2 in ELLIOTT et al., 2013), but it also poses new challenges, particularly that of effective weed control around seedlings during their earliest stages of establishment, since they are tiny, compared with planted saplings (which are usually 30-50 cm tall at planting time) and therefore are exposed to more severe weed competition for longer periods.

Recent advances in several technologies now raise the possibility of automating several restoration tasks, but two technologies are likely to make the greatest contribution: namely UAVs (unmanned aerial vehicles or drones) and computer-aided plant recognition. UAVs overcome the problem of accessing remote restoration sites, whilst imaging and particularly plant recognition systems will provide with the “intelligence” required to enable them to survey restoration sites, locate seed trees, drop seeds into appropriate places, distinguish between herbaceous weeds and trees and monitor restoration results.

AUTOMATING PRE-RESTORATION SITE SURVEYS

The main purposes of pre-restoration site surveys are to determine the extent of existing natural forest regeneration and identify the barriers to its further progression. Such information is needed to write restoration plans. At present, such surveys are carried out using circular sample plots (usually 5 m radius), laid out across the restoration sites. Within each plot, the number and species of natural regenerants (i.e., tree seedlings or saplings taller than 50 cm, and live tree stumps) are recorded, density determined and the number and species of additional trees, needed to be planted, per unit area, to achieve canopy closure within a desirable timeframe, is calculated. Barriers to regeneration, such as signs of fire, cattle browsing and soil degradation are also assessed, to determine site management requirements (ELLIOTT et al., 2013; Chapter 3). Six people can collect data from 10-20 circular plots per day, depending on topography and vegetation density. The number of circles required per hectare depends on the heterogeneity of the vegetation, but 4/ha are usually sufficient for reasonably uniform sites.

Whilst satellite imagery has been used for decades to measure rates of deforestation … “it is unlikely that forest degradation monitoring can be conducted …. with currently available remote sensing data” (MIETTINEN, 2014) and certainly not with the necessary detail, currently acquired through the conventional field survey method described above.

Drone-mounted cameras and other scanning devices, however, certainly do have the potential to provide very detailed data on the extent of natural forest regeneration, as well as the factors likely to be hindering it (detection of charcoal or cattle etc.). Controlled by GPS, they could fly rapidly and directly to pre-determined sampling points and record images, which could later be analysed, either by eye or by computer algorithms, to determine the density of natural regenerants. Such data could be collected in minutes, rather than days, at a fraction of the cost, in terms of labour and transportation. The main limitation of using conventional photography from drones would be detecting the smaller regenerants, overtopped by herbaceous weeds, but with laser scanning technologies now advancing so rapidly and becoming drone-based (CHISHOLM et al., 2013), it may be possible in the near future to "see through" the canopy of herbaceous weeds and even to identify the species of woody natural regenerants beneath (MALTAMO et al., 2014).

AUTO-SEED COLLECTION

For tropical forest restoration projects, conventional seed collection usually involves small groups of seed collectors walking through remnants of the target (or reference) forest ecosystem – relatively intact forest of the type to be restored – looking for trees of the desired species with ripe fruits, which are ready for seed extraction. For forest ecosystem restoration, seeds from at least 20-30 species must be collected. Since different tree species fruit in different months, seed collection trips are usually necessary monthly or more frequently. Gathering seeds from the crowns of tall trees is difficult and may involve laborious and dangerous tree-climbing, or the use of cutters on poles or even catapults. It is much easier simply to collect fallen fruits on the ground, but this results in the collection of a lot of rotten or partially eaten seeds. In tropical forests, conspecific trees are typically spaced far apart, so seed collectors must walk long distances to gather seeds from enough trees to ensure adequate genetic diversity of the planting stock, derived therefrom (forest geneticists recommend collecting from at least 50 trees (BOZZANO et al., 2014), but this is almost never done in practice). Experienced staff tend to return, year after year, to the seed trees that they know, thus further narrowing the genetic base of the planting stock. During a typical days' work, an experienced team of 2-3 seed collectors may gather seeds from perhaps just 5-10 trees.

Clearly such methods will never meet the enormous seed supply necessary for landscape-level forest restoration on the scales envisaged by the UN, even for conventional tree planting, let alone for drone-based aerial seeding, with its potential capacity to deliver tens of thousands of seeds per vehicle per day. Lack of seed supply is now widely recognized as a major factor, limiting ecological restoration using native species (BOZZANO, et al., 2014). A more rapid and cost-effective method to i) locate seed trees with ripe fruit and ii) collect large amounts of viable seeds from them is therefore essential.

Automated seed collection could be developed in several incremental steps. Firstly, it is possible right now to fly drones over forest canopies and to transmit real-time VIDEO back to an observer who could recognize and log the GPS co-ordinates of desired tree species in fruit by eye. The GPS co-ordinates could then be given to seed collectors, who could use hand held GPS units to plan optimum routes through the forest, thus reducing walking/searching time and maximising seed collecting time.

The lower drones fly, the greater the likelihood of spotting fruit-laden crowns of the desired tree species. However, low flight across a forest canopy is hazardous. High-resolution object-avoidance sensors would be needed to enable the drone to respond to the highly heterogeneous topography of a forest canopy and prevent it from colliding with emergent branches.

A system, based on high-resolution still images, taken from low-flying aircraft, has already been developed. On Barro Colorado Island, Panama, LOPEZ et al. (2012) used an identification key from such images, based on the crown typology, contour, architecture, foliage cover and texture, colour and phenology (TRICHON, 2001), to reliably map 22% of the common canopy species. Although errors of omission (missed trees of the target species) were high, this would not matter for seed collection purposes, provided enough seed trees of each species were located to maintain genetic diversity of the planting stock.

The next step would be to develop computer-aided tree crown recognition – not just the species but also the presence/absence of ripe fruit. The main technology, currently being developed, to do this is imaging spectroscopy (or hyperspectral remote sensing), which measures light, reflected from forest canopies, in hundreds of narrow, mostly contiguous spectral bands of visible and infrared wave lengths. The leaves and branches of different tree species reflect different spectral bands to different degrees, so the “spectral signature” of a tree crown can potentially be used to derive its species. Unfortunately, spectral signatures vary considerably among trees within species, often due to the condition of each tree (health, phenophase etc.), slope, attitude, time of day etc., so there may be some way to go before the technique could be used to isolate and identify the species of all the tree crowns in tropical forests, where tree species richness is so very high. However, for seed collection, only a relatively low number of target seed species (20-30) need be positively identified from the general background of “everything else” (and as already mentioned above, failure to identify all trees of the target species is not a problem). BALDECK et al. (2015) seem to have solved these problems, using 167 bands of spectral data in the visible to shortwave infrared range and analysing the data using a single-class classification model (i.e., identifying one kind of object from a diverse background of many other objects) called a "biased support vector machine". With this technique, they were able to recognize the crowns of 3 target species with an accuracy of 94-100%.

Lidar is another recent technology which can be applied to mapping forest canopies and potentially identifying the species of tree crowns. Basically, it involves firing a narrow laser beam to measure the distance between the instrument and the first object that the beam reaches (e.g., leaf, branch, forest floor etc.), by measuring the time taken for the beam to be scattered back to a sensor. At present, it is usually used to complement hyperspectral imagery, to delineate tree crowns and to carry out "orthorectification" (removing the effects of image tilt and terrain), so that hyperspectral data can be accurately matched up with individual tree crowns, but lidar can also add new variables to the data set, such as tree height and crown dimensions, surface texture and architecture, which can contribute towards species identification (LATIF et al., 2014; SINGH et al., 2015).

Until very recently, hyperspectral and lidar sensors were bulky and had to be carried by planes, usually flying around 1,000 m above ground level. However, recently, miniaturized sensors that can be attached to drones have become available[4.] Drone-mounted sensors can collect data much closer to tree crowns and therefore, of much higher resolution, than conventional aircraft can. However, processing such data streams in real time, to enable drones to instantly recognize seed collection trees, currently requires enormous computing power and time, so it may be several years before drones will be able to "recognize" tree species in real time and begin collecting seeds from them immediately. A more likely approach, at least in the short term, would be to use separate drones for locating seed trees and subsequent seed collection. So, two types of drones would be needed: i) those with sensors to locate seeds trees and gather their GPS co-ordinates and ii) those with seed collection apparatus (FLETCHER, pers. com.)

The most difficult part of achieving fully automated seed collection would be the development of drone-mounted tools, capable of removing fruits from tree crowns and the artificial intelligence and object avoidance capabilities, needed to navigate and manipulate objects in a complex (and constantly moving) forest canopy, without drones becoming tangled in foliage. As far as I know, no researchers are currently

[4] www.headwallphotonics.com/blog/bid/336623/Hyperspectral-Sensors-for-UAV-Applications
vespadrones.com/hyperspectral-imaging-latest-sensors-uav-applications/

tackling these challenges, although various ideas have been proposed including robotic arms, suction tubes, rotating brushes and nets (HARDWICK, pers. com.).

AUTO-SEEDING

Since tree saplings are heavy and bulky, they are expensive and difficult to transport to remote sites and to plant robotically. Therefore, it is likely that aerial seeding will be the preferred method to introduce additional trees into deforested sites, to complement natural regeneration. Aerial seeding, from planes or helicopters, has been widely practiced in forestry for many years (NATIONAL RESEARCH COUNCIL, 1981). However conventional aircraft are expensive to run and maintain and require both an airport and a pilot for their operation. Drones offer a cheaper and more practical solution for aerial delivery of seeds into deforested sites and the technology required for aerial seeding by drones is rapidly developing (Figs 1.1 & 1.3).

The most advanced system is being developed by a UK start-up company, BioCarbon Engineering. The company has developed a drone-based remote sensing system to survey restoration sites and construct a planting map to determine which species to plant where. Another drone, guided by the planting map, then propels bio-degradable plastic pellets, containing pre-germinated seeds in a nutrient gel, into the soil from about 1.5 m above the ground. Compressed air is used to fire the pellets into the soil to ensure adequate penetration and the gel protects the germinated seeds from the impact with the soil surface and also helps the seed to stick to the soil. When fully developed, each drone will be able to deliver up to 72,000 seed pellets per day and 6 drones can be simultaneously controlled per operator.

Figure 1.3 – This drone, demonstrated during the workshop field day, uses a simple box with a trap-door to release seeds into deforested sites.

In ecological terms, we may think of such drone-based systems as carrying out the same ecological function as seed-dispersing animals, but doing so at a vastly accelerated rate. Over much of the tropics, the larger animals, which formerly dispersed tree seeds (especially large-seeded climax species) from forests into deforested areas, have been extirpated (e.g., elephants, rhinos, wild cattle, hornbills, large fruit bats etc.). Consequently, artificially replacing their ecological function with drones may be a stop-gap solution until expensive and complex species re-introduction programs can be planned, funded and implemented.

Redesigning the fruit

However, if we are considering replacing seed-dispersing animals with drones, we may need to redesign the "fruits" in which seeds are dispersed.

The purpose of fruits is to aid the dispersal of the seeds contained within away from the parent tree and thus avoid competition with 'mom'. They do this in two main ways. Most tropical tree species have nutritious fruits, which entice animals to swallow their seeds and deposit them far away from the parent tree, after passage through the animal's digestive tract. Other fruits (of fewer species) grow variously shaped 'wings', which slow the descent of seeds when they fall from the parent tree, increasing the chances that they will glide on the wind away from the parent tree, before they hit the ground.

However, if we change the dispersal mechanism of seeds, from wind and animals, to aerial vehicles, then neither of these fruit traits is particularly useful. When carrying out aerial seeding, we do not want the seeds to be consumed by animals, since rodents, which commonly inhabit deforested sites, are mostly seed predators. Therefore, an artificial fruit, designed for aerial deposition, would more usefully surround the seeds with chemicals that deter animals from consuming them. Otherwise, aerial seed drops would merely amount to laying out a buffet for rodents and other seed predators. Chemical repellents have been tested for aerial seeding in forestry since the 1990's (Nuyun & Jingchun, 1995).

Neither would we want artificial fruits to drift sideways; quite the opposite, in fact. Ideally, aerial seeding would be a precise operation, placing the seeds optimum distances apart, to ensure rapid and even canopy closure, across the site, once the seeds germinate and the trees grow up. So, an artificial fruit should be designed more like a dart and not like a glider. Such a "designer seed-bomb" should be engineered to drop straight down, with the minimum of air resistance, achieving terminal velocity as quickly as possible. A sharp point would penetrate the soil and anchor the seed-bomb in place, minimising sideways movement by wind, rain or soil erosion. The ideal penetration depth would place the seed slightly below the soil surface. This would reduce the risk of desiccation. The seed-bomb would be made of a water-soluble material, which would melt away as soon as rain fell, leaving the seed in the best position for germination.

The use of designer seed-bombs also presents a major opportunity in that it would be possible to surround seeds, within the bombs, with a variety of resources that would maximize both germination and early seedling development.

Hydrogel (such as that already used by BioCarbon Engineering) may play an important role in preventing seed desiccation and protecting seeds from the physical forces of impacting the soil at high velocities, as well as providing a medium, in which other substances can be dissolved or suspended. Simply adding forest soil to the hydrogel would probably ensure that the spores of essential symbiotic microbes (e.g., mycorrhizal fungi and nitrogen fixing bacteria) would be instantly available to infect the roots of the germinating seedlings, although commercially available inoculae could also be added. Slow-release fertilizer beads, could also be added to the gel-soil mix to deliver nutrients to the roots of the young seedlings over a prolonged period.

Seed coating technologies are essential for modern agro-industries and many such technologies could be equally well applied to ensure high germination rates of aerially delivered tropical tree seeds. Such treatments need not be expensive or complicated. For example, scientists at King's Park, Perth, have used aspirin as a foliar spray and a seed coating, to dramatically increase the success of restoring vegetation in Saudi Arabia[5]. A dilute aspirin solution enables plants to survive stressful conditions by controlling stomatal opening and thus reducing water loss, as well as assisting in normal membrane functioning and overall water relations. Since desiccation is the main cause of mortality amongst direct-seeded tropical forest tree seedlings, aspirin could provide a cheap and effective way to reduce such losses.

AUTOMATING WEED CONTROL AND FERTILIZER APPLICATION

Auto-weeding is perhaps the Achilles' heel (or Holy Grail?) of AFR. If forest tree seeds could germinate and the resulting seedlings grow well in deforested sites, then forest restoration would be unnecessary, because ecological succession would proceed, from the, in-coming seed rain. But this does not happen, because on open, sunny deforested sites, herbaceous weeds compete with the young, small tree seedlings for light and nutrients and they also provide fuel for fires, which kill young

[5] www.sciencewa.net.au/topics/environment-a-conservation/item/3464-aspirin-aids-middle-east plant-restoration-project/ 3464-aspirin- aids-middle-east-plant-restoration-project

trees but not the fire-resilient herbs. Weeding is therefore essential. When restoring tropical forest ecosystems conventionally, nursery-grown tree saplings are planted out (to complement natural regeneration), when they are about 30-50 cm tall. Before tree planting, restoration sites are cleared of herbaceous weeds by slashing and applying a non-residual, systemic herbicide to kill the weed roots, without disturbing the soil. During site preparation, great care must be taken not slash or spray existing natural regenerants. After planting, weeding is continued at 4-6-week intervals during the rainy seasons for 2-3 years after which, canopy closure is usually sufficient to shade out further weed growth. Weeds, growing close to sapling stems, must be pulled by hand, since use of metal tools might damage the tree roots. Hoes are then used to clear a wider circle around the planted trees and final a mechanical weed cutter is often used to slash weeds between the trees. Cut weeds are used as a mulch around the trees. This shades the soil surface, inhibiting weed seed germination, helps to conserve soil moisture and encourages development of soil fauna communities around the planted trees (ELLIOTT et al., 2013; Chapter 7).

Use of herbicides after tree planting has been problematic, since broad spectrum herbicides can kill the trees, along with the weeds. Most weed growth occurs during the rainy season, when wind and rain create problems for herbicide use. Wind often blows the herbicide spray on to the trees and it is difficult to train workers to prevent this from happening. Furthermore, frequent showers limit the window of opportunity for herbicide application, since rain dilutes herbicides, rendering them ineffective.

Close to the trees, merely slashing weeds is not enough. Although it reduces above-ground competition for light, it actually increases below-ground root competition for water and nutrients, because slashed weeds absorb more of these resources as they regrow. So, manual weeding must include pulling or digging out weed roots. It is very tough work and field workers are unlikely to do it, unless closely supervised and if the work is not carried out carefully, weeding tools slash through tree stems or roots.

Weeding is the most expensive task of forest restoration. Automating it would enable restoration of inaccessible sites and considerably reduce costs, but it is by far the most difficult of all restoration tasks to automate.

If tree seedlings are to grow *in situ* from aerially-delivered seeds, the seedlings will be very small for a long time. Even weeding them by hand would be difficult; let alone coming up with an automated technique. Weeding would be required for at least an extra year (compared with conventional tree planting), before the trees become established (the establishment point being when the sapling crowns overtop the weed canopy and their roots penetrate below those of the weeds).

However, there are four avenues of research that might contribute to the development of auto-weeding techniques: i) determine which forest tree species are most able to compete with herbaceous weeds, ii) identify herbicide-resistant trees, iii) develop more selective herbicides and iv) smart spraying.

Research suggests that some tree species may perform considerably better than others, when planted into weedy sites. In northern Thailand, we found a handful of species that compete well with weeds, when planted out as saplings; nearly all light-loving pioneer species e.g., *Erythrina subumbrans, Melia toosendan, Gmelina arborea, Spondias axillaris & Hovenia dulcis* (FORRU, unpublished data). Furthermore, TUNJAI (2005), working on direct seeding in the same area, reported that weeds might actually nurture seedlings of several direct-seeded species, by shading them and reducing desiccation. Weed removal had no significant effect on or actually reduced survival and growth of young seedlings ($P<0.05$) of all but one of the 12 species she tested (6 from upland evergreen forest and 6 of lowland deciduous forest). Therefore, it might be possible to devise a system whereby drones carry out aerial seeding of the most weed-resistant, pioneer tree species, to achieve canopy closure and eliminate weeds, whilst establishment of shade-tolerant, late successional species is achieved by natural seed dispersal or by subsequent aerial seeding of those species.

Glyphosate is the most widely used herbicide in forest restoration. A systemic, non-residual herbicide, it is a highly cost-effective method of weed control. Compared with manually cutting weeds, at a riparian site in Brazil, glyphosate increased the growth of planted trees 2-6-fold and increased the species diversity of both woody and herbaceous plants (by removing dominance), at 57% of manual weeding costs. Glyphosate (and its metabolites) were not detected in soil or runoff water, but were present in runoff sediments (FLORIDO et al. 2015). However, if UAVs were to spray glyphosate indiscriminately, both trees and weeds would be killed, unless the species or genotypes planted were glyphosate resistant.

Glyphosate resistance has been genetically engineered in crops and occurs naturally among populations of weeds of agricultural fields, where the chemical has been used for many years. In crops, glyphosate resistance is achieved by manipulating a single gene, whereas natural evolution of resistance in weeds probably depends on changes in several genes (DUKE & BOWLES, 2009). Therefore, within any seedling population of a forest tree species, it is likely that some genotypes may be resistant to glyphosate, although the frequency may be exceedingly low. Experiments could therefore be devised to grow large numbers of seedlings, of diverse genetic origins, in nurseries and spray them with glyphosate to identify naturally resistant plants and then grow them to establish seed orchards of genotypes that are resistant to glyphosate. It would then become possible to carry out aerial seeding and perform weeding by aerial spraying, with a relatively safe and widely available herbicide. The main flaw with this approach is that, although the trees established by aerial seeding would be glyphosate resistant, any natural regenerants would not be. So, blanket aerial spraying with glyphosate would destroy any contribution that pre-existing natural regeneration might have made towards canopy closure. The very large numbers of seedlings that would have to be grown to identify resistant genotypes may also preclude this approach.

Another way might be to use existing more specific herbicides or develop new ones. Basically, herbicides can be classified as grass-specific (graminicides), broadleaf-specific (kill or inhibit herbs and tree seedlings but not grasses) and non-specific (kill or inhibit most green plants). Glyphosate belongs the last group. Graminicides are already used in forestry (CLAY et al., 2006), although they are only useful where grasses dominate the weed flora. Furthermore, they not as effective as glyphosate at controlling *Imperata cylindrica*, the most widespread of the grass species that inhibit forest succession in SE Asia.

Highly selective herbicides have been developed that exploit biochemical differences between even closely related species. For example, nicosulfuron, does not kill maize (which metabolizes the chemical to a harmless form) but it does kill other closely related grass species and herbs. So, the possibility exists that highly selective herbicides could be developed for forest restoration purposes. What is needed is a "magic bullet"; an herbicide that kills herbaceous plants but not woody ones, is safe to use and has no adverse effects on the environment. Currently no such chemical exists, but one approach might be to investigate the allelochemicals produced by the weeds themselves to develop "bioherbicides" (see Chapter 11). Such chemicals are synthesized by weedy herbs to gain a competitive advantage over other weed species, so it is likely that some of them could be combined in a "cocktail" that would kill weeds without harming tree seedlings. Allelochemicals are also well known from some pioneer tree species (e.g., *Gmelina arborea* (RAMAKRISHNAN et al., 2014)). Such tree species could also be analysed for the development of herb-specific bioherbicides or simply making sure they are well-represented among the tree species planted could ensure that weeds do not cause plantation failure. The problem with developing more specific herbicides is that research and testing needed will most likely take many years, before useful products emerge.

In the meantime, more accurate and "intelligent" spraying of existing herbicides might provide a solution. Smart spraying would involve developing drones that can carry canisters of herbicide; perhaps several kinds. A plant-recognition system would be used to distinguish between herbaceous weeds and tree seedlings/ saplings and then the drone would deliver herbicide onto the weeds, but not onto trees.

"Machine vision" systems for detecting weeds for agricultural and horticultural purposes, began to emerge in 1990's, (THORP & TIAN, 2004) and have advanced considerably since then. Such systems are capable of distinguishing between crop plants, weeds and bare soil, so that herbicide can be sprayed on to weeds, without killing the crop, or wasting chemicals on bare soil. More recently, Thomas Wilder and Cynthia Johnson[6] demonstrated a drone-based weed control system using a HANA database, populated with weed types to identify weeds via an infrared sensor. One of several herbicides was dispensed directly onto each weed, based on weed species, size and strength of solution needed. Ground vehicles, capable of auto-weeding between rows of crop plants, are already available7 (BAKKER et al., 2006).

Drone-based weed recognition could perhaps make use of the close-up plant-recognition systems, now available as phone apps, such as Pl@ntNet[8] & Leafsnap[9] (see Chapter 11). These systems compare plant photos, taken with smart phones, with a database of known images and use pattern-matching algorithms to identify species. In fact, a drone-based weed-detection system for AFR would not need this level of detail. The most basic version would only require an on-board capability of distinguishing between woody and non-woody plants in real time, to trigger a spray/ no-spray response. If drones carried both a grass-specific and a broadleaved specific herbicide, in separate canisters, then an ability to distinguish between grasses, other weeds and woody plants would be needed, but this is still a much simpler computational process than the identification of individual plant species, which has already been achieved to a large extent by the phone apps.

Drones that spray chemicals on agricultural fields are now becoming commonplace (Fig. 1.5), but for AFR, we would need to develop far more directed and precise herbicide delivery systems than those used in agriculture. Drones must be capable of operating at very close quarters to both the weeds and the very young trees growing up among them, without become entangled in the vegetation and without spraying herbicides on to small tree seedlings. This is undoubtedly the most challenging of all AFR tasks (Fig.1.4).

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6 http://events.sap.com/teched/en/session/13694

7 http://sydney.edu.au/news/84.html?newscategoryid=2&newsstoryid=13686

8 http://m.plantnet-project.org/

9 http://leafsnap.com/

AUTO-MONITORING – RECOVERY OF VEGETATION AND WILDLIFE

Monitoring should be an essential part of all forest restoration projects, not only to assess success, but also to learn from mistakes. If weeding is the most difficult of restoration tasks to automate, then monitoring is perhaps the easiest. The key measurable milestones, of tropical forest restoration are firstly canopy closure (the point at which forest canopy shades out herbaceous weeds – also known as "site recapture"), then the development of forest structure (multiple canopy layers, including an understorey, composed of tree seedlings and saplings, which indicate self-perpetuation of the ecosystem) and finally, recovery of biodiversity levels, similar to those within the target (or reference) forest ecosystem, including the return of key species that are typical or representative of that ecosystem.

Canopy closure is already easily detectable with satellite imagery and aerial photography, from both conventional aircraft and drones and the plant identification technologies, already described above, could also be used to assess recovery of plant species richness and diversity.

Drone-based lidar (also already mentioned above) is an excellent technology for monitoring the recovery of forest structure, due to its ability to create detailed 3D maps of the forest (WALLACE et al., 2012). It can also be used to monitor recovery of carbon stocks (CHISHOLM et al., 2013) (see Chapter 13), an essential activity if AFR projects are to be funded under REDD++. Similar results can now also be obtained with an image processing technology called "Ecosynth"10, which uses large sets of overlapping digital photographs, taken with drone-mounted cameras (ZAHAWI et al., 2015), which are then processed with 'structure-from-motion' algorithms, to create 3D point clouds. Each point in the clouds is defined by its horizontal and vertical co-ordinates, together with red–green–blue (RGB) colour data. The point clouds can then be used to estimate the height, structure and roughness of forest canopies. Although the point clouds and the information derived therefrom are similar to those obtained with lidar, Ecosysnth does not require the generation of laser beams and special sensors. It uses ordinary digital cameras and open-source software and is therefore likely to be cheaper than lidar and more practical.

Drones may also provide impetus for greater community involvement in monitoring forest restoration. PANEQUE-GÁLVEZ et al. (2014), explored the feasibility of using small drones for community-based forest monitoring (CBFM). They found that use of drones enhances CBFM and would be feasible in many locations throughout the tropics, provided suitable funding and training are made available to communities. They suggested that the use of small drones can help tropical

[10] http://ecosynth.org/

communities to better conserve their forests, particularly for biodiversity conservation and climate change mitigation projects, such as REDD++.

Biodiversity recovery is one of the central aims of forest ecosystem restoration, not only the achievement of species richness and species diversity levels, similar to those of the target (or reference) forest, but also the return of key species that are representative of the target forest and their use of the restored forest as breeding habitat. In short, it is the animals, not humans that decide whether or not restoration has been successful.

Biodiversity assessments have been attempted by using drones, indirectly, to predict biodiversity levels via correlations with the development of forest structural complexity. Digital photography from drones has also been used to visually confirm the presence of key animal species, such as orang-utans (KOH & WICH, 2012), but, in dense tropical forests, very few animals are visible to conventional drone-mounted digital cameras. Therefore, thermal imagery, which is capable of detecting animals beneath the forest canopy, is now being developed to detect and identify animals (CHRISTIENSEN et al., 2014).

At ground level, digital camera traps have been used since 2006 to capture wildlife images. However, since AFR is aimed at remote and inaccessible sites, regularly retrieving data from camera traps and replacing their batteries would be a laborious process. Fortunately, camera trap technology is advancing rapidly. The latest models can now upload photos via cellular telephone networks and their batteries are rechargeable via solar panels, so once installed, no further visits are required, until the cameras are retrieved[11.] Outside the range of cellular telephone networks, drones are now being used to retrieve images from camera traps, by functioning as "data mules". For example, the Wadi Drone, developed by four NYUAD students MARTIN SLOSARIK, TING-CHE LIN, VASILY RUDCHENKO, KAI-ERIK JENSEN, is a fixed wing airplane with a 2.5-metre wingspan. It automatically retrieves images from cameras, via Wi-Fi, when the drone flies within 300 m of them12.

Birds are harder to see but easier to hear and bats are also more readily detected by audio. So, remote auto-surveys of birds and bats might be possible by placing arrays of microphones (autonomous recording units or ARU's) across restoration sites and identifying species by the sonograms recorded by them (DUKE & RIPPER, 2013). By measuring the differences in the times at which the bird song arrives at different microphones, it is possible to triangulate the positions of the birds and

[11] wildlifenews.co.uk/2013/06/new-product-solartrail-solar-powered-camera-trap/
www.reconyx.com/shop/PC900C_Cellular_HyperFire_Professional_Covert_IR/d/358/56

[12] wadi.io/?page_id=90

create a dynamic map of bird territories across the restoration site and thus derive population density estimates (LUCAS et al., 2015).

With these technologies, it is become increasingly more feasible to monitor the recovery of both plant and animal diversity, remotely, in forest restoration sites. All we need now are drones, capable of delivering and retrieving cameras and microphones from restoration sites.

THE ULTIMATE VISION?

Imagine an expansive, deforested landscape - rugged terrain that has been designated as a restoration area, to contribute towards climate change mitigation and biodiversity conservation. Lorries arrive at the nearest access point. Drones, solar panels and large tanks of herbicides are off-loaded and a secure base station is established. The solar panels are connected to batteries, which are themselves connected to electromagnet induction pads, where the drones charge up their batteries, by landing on the pads[13.]

Drones, carrying various imaging devices, fly off to survey the restoration sites, recording the topography, weed cover and the density and species of natural regenerants. The data, returned to a central computer, is used to design the restoration program, including weed control, and to calculate the number and species of seeds to drop into the restoration sites, to complement any natural forest regeneration that may already be occurring.

Next, drones that can spray herbicides and distinguish between weeds and trees clear the restoration site of weeds, whilst avoiding natural regenerants. When battery power, or the herbicide in their canisters, run low, they return to the base station, recharge themselves on the electromagnet induction pads and refill their herbicide canisters from the base station tanks. Multiple recharge/refill stations could be established around the project area to increase the drones' range.

Meanwhile, other drones fly to the nearest remnant of relatively undisturbed forest (the target or reference ecosystem), where they find seed trees of the required species. They are followed by seed-collection drones, which, using various attached tools, collect fruits from the trees and return them to the base station. Seeds are extracted from the fruits and put into designer seed-bombs, along with soil, hydrogel and various other assistive substances. The bombs are loaded into delivery devices, attached to aerial-seeding drones, which then fly off to seed the sites. After seeding, weed-control drones then continue to detect weed growth across the site and spray herbicides where and when necessary.

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[13] http://skysense.co/

Once the tree seedlings grow big enough to be detected, monitoring drones fly out to count them and assess survival rates and eventually canopy closure and the development of forest structure with lidar and/or structure from motion technologies. Finally, drones drop autonomous recording units and camera traps into the restored forest to record the return and breeding of wildlife species – the final indicator of restoration success, sending their data back to the base station via telephone signals or data mule drones. Once the project is complete, the lorries return, are loaded up with the drones, tanks and solar chargers and drive on to the next restoration project area.

The operation would be co-ordinated by a central computer, which determines the priorities of the tasks required and assigns tasks to each drone. Ideally the various devices used for different restoration tasks should be interchangeable among the drones so that, for example, a seed collection drone could be converted into a weeding drone, by detaching the seed collection tools and attaching herbicide canisters. In this way, the minimum number of drones would carry out the maximum amount of work, regardless of the different tasks required each day and no drones are left idle.

THE NEXT STEPS

Of course, the above vision is still very much a dream (like conventional tropical forest restoration was 30 years ago); but it is not unattainable. Most of the technologies, required to realise it, are already available or under development. All that is needed is their integration and combination with sound restoration science, in innovative ways.

Many challenges remain. Drone technologies are still in their infancy. The flight ranges of drones are limited by battery life, even if the drones could auto-recharge themselves in the field. So, increasing battery life will be essential. Fortunately, battery technologies are advancing rapidly, hydrogen fuel cells have now extended the flight times of drones to several hours[14], so we may not have too long to wait before long distance drone flights will become routine. Another problem is that drones are fragile devices and cannot fly in rain, so "ruggedization" of the technology is another priority. Lifting power must also be increased.

As with all new technologies, costs are currently very high, although they are rapidly declining. For example, early mass-produced drones cost several thousand dollars, but can now be bought for just a few hundred dollars and simple radio-controlled drones to carry out basic visual survey tasks can be bought for as low as

[14] www.bbc.com/news/technology-35890486

50 US$. The first camera traps, capable of transferring images via the cellular phone system started at over 1,000 US$, but similar models can now be bought for just 170 US$. Nevertheless, the costs of all the technologies described above still have a long way to fall before AFR becomes a viable proposition to funders.

AFR will only be achieved through intensive cooperation among ecologists and technologists, with widely diverse backgrounds and fields of interest, but united by the imperative to restore Earth's tropical forests, to mitigate climate change, conserve biodiversity and maintain their supply of environmental services and forest products to humankind. Multidisciplinary collaboration is the key.

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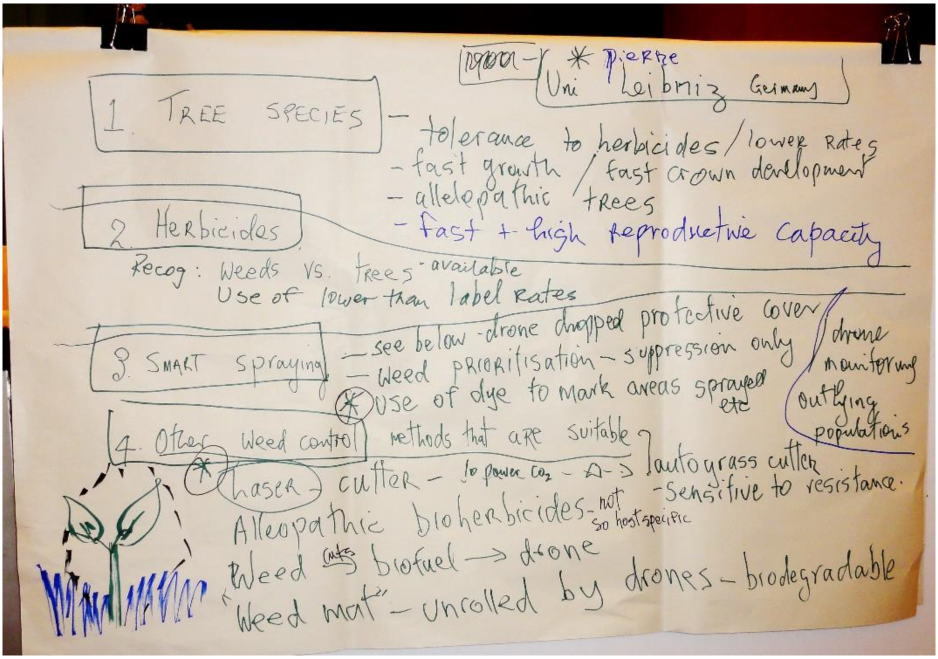

Figure 1.4 - Of all the discussion groups in the workshop, the debate on how to automate weeding probably generated the most innovative ideas.

Figure 1.5 – Birds' Eye View (a local Chiang Mai company) demonstrated a drone, capable of spraying pesticides, during the field day

Figure 2.1 – Photo from a UAV, of a forest restoration site, Ban Pong Krai, Chiang Mai Thailand. White dots in the image are ground markers (Photo by FORRU's DJI Phantom 4 Pro).

Figure 2.2 – Forest fire detections from UAVs (modified from Cruz et al., 2016)

Chapter 2

UNMANNED AERIAL VEHICLES FOR AUTOMATED FOREST RESTORATION

***Pimonrat Tiansawat*[1] *and Stephen Elliott*[1]**

ABSTRACT

Unmanned aerial vehicles (UAVs) have been gaining in popularity and are used in many fields, including biodiversity conservation. They are currently available in many sizes and forms, and they can be used for aerial photography, mapping and monitoring natural resources. To use UAVs for automated forest restoration (AFR), technologies involved must be advanced and adapted, to perform the specific tasks required, particularly aerial seeding and maintenance procedures, such as weed control and fertilizer application. Getting UAVs to function fully autonomously, when performing such tasks, will be challenging. Integrative research, among engineers, computer scientists and ecologists, is needed to advance the AFR concept and the drone-based tools needed, to bring the concept to fruition.

Key words: drone, mapping, aerial seeding, aerial monitoring, power source, obstacle avoidance

INTRODUCTION

An unmanned aerial vehicle (UAV) is a flying device, with no pilot on board, which is controlled remotely, or flown autonomously, following a computer program. The basic components of UAVs include the body, computing components, a power supply, sensors that detect position and movement, software, flight controls, actuators, loop principles, a communications device and mounted payloads e.g., cameras n other sensors. Nowadays, several types of UAVs are available: rotary (multi- or single-) (Figs. 2.4 & 2.6), fixed-wing, and hybrids (Fig. 2.3). Each type is suited to perform specific functions. Although the first UAVs were pilotless planes, developed for military purposes, as early as 1900, modern UAVs have been used for various civilian applications, such as land-use planning, archaeological surveys, hobbies, and environmental and conservation tasks. In this review, we use the term UAV for the vehicles and UAV technologies to encompass ground control stations, communications and supporting equipment to operate flights.

The use of UAVs for automated forest restoration (AFR) is becoming more common among the research community. UAV technologies can be used to perform

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various tasks required to implement forest restoration, from site surveys (Fig. 2.1), to the development of restoration plans, site preparation, delivery of seeds and/or seedlings to the site, site management (i.e., weeding and fertilizing) and surveys for biodiversity recovery following restoration interventions (ELLIOTT, 2016) (Table 2.2). However, to achieve the goal of automated forest restoration, several specialized UAV technologies must be developed to perform specific tasks. Therefore, this chapter examines activities relevant to forestry applications, including those that are already achievable and those that might be achievable in the near future, and discusses challenges to developing UAVs for AFR.

CURRENT USE OF UAVs IN CONSERVATION

Forest mapping and monitoring

It has only been about two decades since UAVs gained attention in the forestry sector. The primary focus of UAV research has been on mapping and monitoring of forest stands (e.g., ABER et al., 1999 & 2002; DUNFORD et al., 2009; JAAKKOLA et al., 2010; SAARI et al., 2011; MAKYNEN et al., 2012; WALLACE et al., 2012; LISEIN et al., 2013; ZAHAWI et al., 2015; OTA et al., 2017) (Fig. 2.1). UAVs, have become ideal platforms to collect data and visual information from target areas using various payloads, including cameras and other sensors, Mapping and monitoring of forests normally require imaging sensors, a position sensor (i.e., Global Position System: GPS) and an Inertial Measurement Unit (IMU) (a combination of accelerometer, gyroscopes and sometimes a magnetometer).

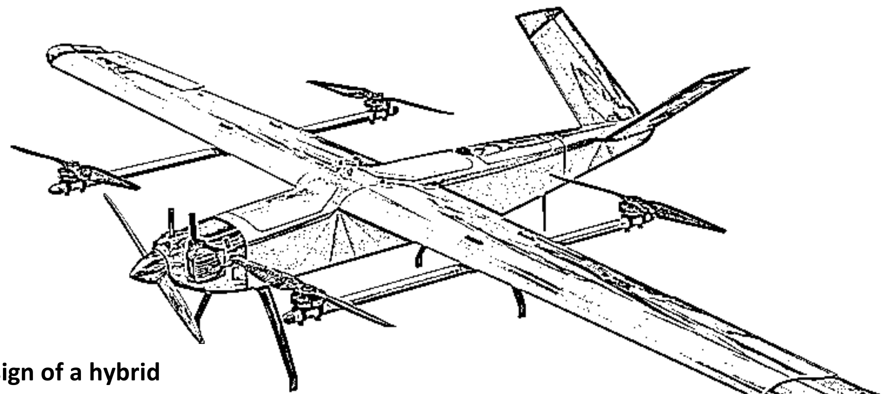

Figure 2.3 – design of a hybrid UAV that is capable of a vertical take-off and landing.

The most widely used imaging sensors are digital cameras sensitive to the visible spectrum (RBG cameras) (Fig. 2.1). HORCHER & VISSER (2004), pioneers in the use of small UAVs for forest imaging, reported that creating forest and stream maps with high-resolution images (8 cm per pixel) is possible using UAVs. Using more detailed and advanced mapping software, three-dimensional (3D) models of target areas can be constructed, using images and other data obtained from UAVs (REMONDINO et al., 2011). Additional sensors can be used, complementing or replacing RBG cameras, to acquire data for forest mapping such as: Light Detecting and Ranging (Lidar) systems (also called laser scanners) (e.g., NAGAI et al., 2009; JAAKKOLA et al., 2010; WALLACE et al., 2012), multi- or hyper-spectral cameras (Fig. 2.4) and thermal sensors (e.g., BERNI et al., 2009; MAKYNEN et al., 2012; SMIGAJ et al., 2015).

The complementary data, acquired by such sensors, allows performance of more detailed analyses, to gain a more detailed understanding of forest structure. Investigations using such technologies have covered such broad topics as plant water-stress (ASNER et al., 2016), diseases (SMIGAJ et al., 2015), and other aspects of plant health (CALDERÓN et al., 2013). In addition to digital RBG images (Fig. 2.1), hyperspectral cameras (Fig. 2.4) can capture images using the near-infrared (NIR) spectrum. Combining data from the visible and near infrared spectra allows calculation of the Normalized Difference Vegetation Index (NDVI) and analyses of vegetation cover and health (LI et al., 2014). Chapter 3 provides more details about the uses of sensors for mapping and recognizing tree species.

Figure 2.4 - A UAV, equipped with hyper-spectral camera for research in Belgium (CARGYRAK, 2016)

With recent advances in positioning and imaging technologies, small UAVs are being used increasingly to map tree crowns and identify tree species (LISEIN et al., 2015; BAENA et al., 2017) (Fig. 2.7), estimate biomass (ENGLHART et al., 2013), map canopy gaps (GETZIN et al., 2014) and monitor fallen trees (INOUE et al., 2014) (Fig. 2.8).

Forest fire surveys

UAVs have also been used as sensor platforms to monitor forest fires (AMBROSIA et al, 2003; HINKLEY & ZAJKOWSKI, 2011; CRUZ et al., 2016) (Fig. 2.2), carrying either non-thermal infrared micro-cameras, imaging in the far infrared band (7-14 µm) (CASBEER et al., 2006; MERINO et al., 2012), or thermal infrared cameras, combined with IMUs and GPS collecting navigation and positioning data. Such UAVs usually send their data remotely, for immediate image processing at ground stations. Images are processed to minimize errors and to extract fire-contour information (fire perimeter) (Fig. 2.2). Data are fed into models to detect fires (CRUZ et al., 2016), predict their spread and plan appropriate fire-fighting options (MERINO et al., 2012). Single or multiple UAVs (cooperative) can be used to track the fires. Where fires become extensive, simultaneous deployment of multiple UAVs is needed, to update large amounts of information in near real-time (CASBEER et al., 2006).

Wildlife surveys

UAV technologies can also be used to detect wildlife habitats and estimate the abundance of wild animals and plot their distribution. Compared with satellite remote-sensing and ground surveys, the advantages of using UAVs include cloud-free images and lower cost (KOH & WICH, 2012). Moreover, aerial surveys by UAV can be conducted more frequently, to gather data for long-term monitoring. UAVs can be used both for taking photographs and for detecting radio-tagged animals. As camera platforms, they been successfully used to count and map the distribution of several large terrestrial animals (e.g., KOH & WICH 2012; VERMEULEN et al., 2013; BARASONA et al., 2014). VERMEULEN and his team (2013) used a fixed-wing drone, equipped with GPS, IMU and cameras to survey elephants (*Loxodonta africana*) in southern Burkina Faso (Fig. 2.5). The flight was fully autonomous and, at a height of 100 m, high enough for the elephants to appear unaware of the drone’s presence. In Sumatra, Indonesia, a fixed wing drone successfully detected orangutans (*Pongo* spp.) and Sumatran elephants, flying 80-100 m above ground (KOH & WICH, 2012).

In addition to photography, UAVs can receive signals from animals that have been tagged with a radio transmitter (e.g., POSCH & SUKKARIEH, 2009). For example, a multi-rotor UAV, equipped with an antenna, was used to locate radio-tagged Noisy Miners (*Manorina melanocephala*) in Australia (CLIFF et al., 2015). The study showed that detection by UAV can be achieved both manually and autonomously. The main limitation of the technique was short flight time and inaccuracy, due to movements of birds (CLIFF et al., 2015). To mainstream UAV technologies for wildlife research, it is crucial to investigate the potential impacts of UAVs on target animals (e.g., DITMER et al., 2015).

UAV APPLICATIONS FOR AFR

To use UAVs to perform particular AFR tasks, task-specific hardware and software will be needed. Although currently available technologies, including imaging and positioning sensors, have allowed UAVs to perform rudimentary pre-restoration site surveys, locate seed trees (with partial success) and monitor some aspects of biodiversity recovery (large animals), a great deal of further research will be needed as well as development of a broader range of drone-mounted tools, if UAVs are to play a more universal and routine role in AFR. The need for three technologies immediately spring to mind: robot arms, guided by visual systems, capable of collecting seeds from tree crowns, seed delivery devices, capable of deploying seeds of multiple species of widely varying seed sizes, and “intelligent” spraying systems for weed control (Fig. 2.6). Although research is on-going, no working prototypes of these technologies currently exist.

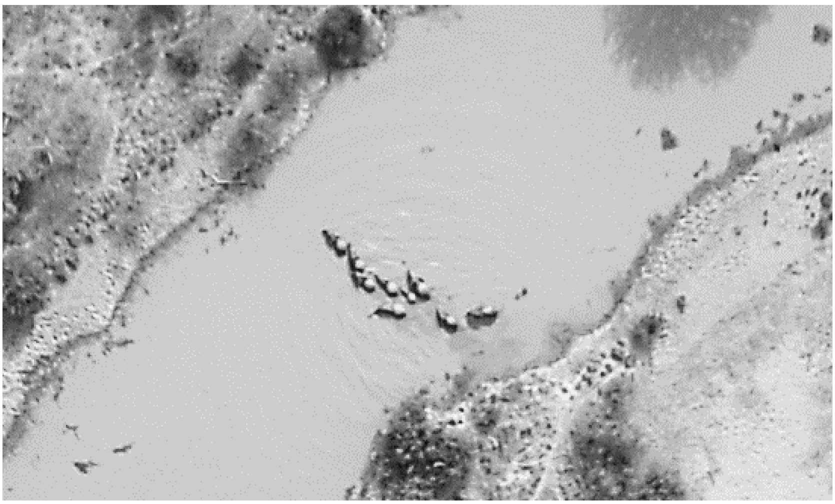

Figure 2.5 - Aerial image from a fixed-wing UAV, 300 m above ground, shows a group of elephants (modified from VERMEULEN et al., 2013).

Table 2.1 - AFR tasks and examples of task-specific hardware and software needs. *Italics* indicate items that will require more research and development.

AFR	Specific tasks	UAVs	
		Hardware	**Software**
Pre-site survey	Locating systems*	GPS, IMU unit	GPS software
	Imaging*	Cameras, other sensors	-
	Site evaluation – level of degradation	Cameras other sensors	*Databases and systems to process the images and decision making*
Seed collection	Locating seed trees	GPS, IMU unit	GPS software
	Plant recognition	Cameras, other sensors	*Databases and on-board processing*
	Seed collecting	*Robotic arms, cutting devices and seed storage*	*Systems to control the robotic arms (cutting mechanisms) and detecting the number of seeds UAVS can handle*
Seed delivery to target restored sites	Seed storage	*Seed containers*	-
	Aerial seeding	*Seed dropping device*	*Systems to control drop-ping patterns and to detect empty containers*
Fertilizer and/or herbicide application (maintenance)	Seedling recognition	Cameras, other sensors	*Databases and on-board real time processing and decision making*
	Fertilizer/herbicide application	*Containers for fertilizers/herbicides with appropriate application devices*	*Systems to make real-time on-board decisions, to control application patterns and to detect empty containers*

** All AFR tasks require location and imaging systems. Here, we include detection at the beginning and do not repeat for the rest of the table*

An overview of technologies already existing and required for further development is presented in Table 2.1. The size and weight of the drone-mounted tools will drive the development of new UAV designs to carry them and power-supply technologies, not only to fly the UAVs, but also to operate the attached devices for reasonable flight times. Site surveying and monitoring may not require large UAVs, because their main payloads will be cameras and sensors that have already been miniaturized. However, the robot arms, seed hoppers and tanks of fertilizer or herbicides are likely to be heavy and require large drones and power supplies well beyond the capacity of those currently in use.

Towards autonomy

Current UAV decision-making tools allow UAVs to fly autonomously only within predefined limited locations (ATHERTON, 2017). Many gaps in knowledge and technologies remain to be filled, before truly autonomous UAVs can be deployed to perform forest restoration tasks. Considerable improvements in power-supply systems, autonomous charging and advanced object-avoidance systems will be essential to enable UAVs to perform basic AFR tasks autonomously.

On-board power source

The power supply determines the flight time, and consequently the range, of UAVs. Typically, the power supply and fuel of large UAVs (>1,000 kg) constitute approximate 40-65% of their weight (NATIONAL RESEARCH COUNCIL, 2000). Smaller UAVs are powered by batteries, most commonly rechargeable lithium-ion polymer (LiPo) batteries. Therefore, the flight time and range of UAVs depends on battery capacity, discharge rate and average amp draw from the battery. LiPo batteries are favoured for UAVs, because of their thin shape and high discharge rates.

With current consumer-level battery technology, UAV flight times range from few minutes to 30 minutes (for 5-kg UAV). For AFR, particularly in remote large areas, much longer flight times will be needed, to make the use of drones practicable. This may be achieved by improving existing lithium-based technologies, but more likely, it will involve development of new power-supply systems. For example, prototype hydrogen fuel-cells have been used to successfully power UAVs for several hours (SWIDER-LYONS, 2016). Moreover, fuel-cell powered UAVs are quieter than those powered by regular batteries; they vibrate less during flight, are easier to control and have net zero emissions (SWIDER-LYONS et al., 2013). In 2004, The Naval Research Laboratory (NRL) of the United States of America successfully flew a hydrogen-fuel-cell-remote-piloted UAV for three hours and 19 minutes (flight weight 1.7 kg) (STROMAN et al., 2006): a record beaten recently by a team in China[2] who achieved a flight time of >5 hours.

Wireless charging

If LiPo batteries, with their relatively short flight times, remain the most affordable UAV power source, then automated wireless charging could be a way to maintain drone flights for AFR tasks in remote areas. Several companies are working on this, with varied approaches.

Charging pads have already been developed for small UAVs (e.g., SKYSENSE INC.). Skysense INC's charging system consists of a rugged, weather-resistant, stainless-steel plate, on which UAVs land. UAVs are retrofitted with charging devices on the legs. These transfer charge to the batteries, as soon as the charging devices come into contact with the steel plate. Charging proceeds automatically, regardless of position, dimension and orientation of the drone[3].

Another technique, being explored, is magnetic resonance (JUNG et al., 2012; KESLER, 2016; SOLACE POWER INC., 2017). A UAV (the receiver) and a charging station (the energy source) are both equipped with copper coils. Once a UAV lands on or hoovers above the landing pad, the coils in the landing pad are turned on. An added feature of the station would be robotic arms to help align the UAV coils with the pad's coils. When the coils attached to the UAV are close enough to the pad's coils, a magnetic field is created and the UAVs battery is charged through electromagnetic induction. After charging is complete, the UAV signals the landing station to cease charging, and the drone can fly away and continue working.

The use of high-power lasers, to charge UAVs, is also being investigated (POWERLIGHT TECHONOLOGIES INC., 2017). With this method, UAVs are fitted with photovoltaic (PV) receivers. The UAVs hover over charging stations, where they are precisely aligned automatically using laser-tracking systems. The charging laser is then aimed at the PV receiver, where laser energy is used to charge the battery, while the UAV continues to hover. The ability to charge drones without landing them is obviously advantageous, where vegetation might obstruct safe landing. One limitation of this method is its high cost; high-power lasers are currently very expensive. However, as with other new technologies, costs are expected to fall, as the technology evolves for commercial use (POWERLIGHT TECHNOLOGIES INC., 2017).

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[2] https://www.intelligentliving.co/hydrogen-fuel-drone/
[3] https://skycharge.de/charging-pad-outdoor

Another approach is to build ground stations, equipped with robotic arms, capable of swapping batteries. An Israeli company, named Airobotics, has developed a ground station with this battery-swap approach (AIROBOTICS, 2018). The system includes a 45-kg box that can be opened at the top. The UAV and ground station are equipped with sensors and communicate with each other. The UAV is also equipped with GPS, cameras, and sonar sensors for navigation and landing on the ground station. The ground station can help guide the landing, using its sensors and a radio signal. Upon landing, a robotic arm replaces the discharged battery with a fully charged one. Up to 10 batteries can be stored in each ground station.

However, all these technologies require power, and in remote areas, where forest restoration is most likely to occur, there is usually no mains electricity. Therefore, in the context of AFR, all these charging stations are most likely to be run on solar power; solar panels feeding electricity into large on-site batteries. Once set up, solar power systems require little maintenance. Therefore, they are the most promising power source to drive autonomous AFR systems.

Powering UAVs directly by on-board solar energy has also been attempted, but not very successfully as yet. Titan Aerospace developed a prototype, solar-powered, fixed-wing UAV in 2015, design for sustained, high-altitude flight, to deliver internet connectivity over wide areas. At 15 m in length and with a wing-span of 50 m, it was anticipated that the Solara 50 would carry payloads of up to 32-kilogram and be capable of continuous flights lasting up to five years. The first and only flight of the Solara 50 was in 2015 in New Mexico, USA. Unfortunately, the left wing suffered a structural failure, shortly after take-off, and the vehicle crashed (NATIONAL TRANSPORTATION SAFETY BOARD, 2015). The project was subsequently shelved.

Using multiple UAVs for forest restoration tasks

As already stated above and summarized in Table 2.1, various, highly specialized, drone-mounted tools will be required to perform the various tasks that comprise an AFR project from start to finish, from robot arms to collect seeds, to herbicide spraying devices. This gives rise to two approaches to drone development for AFR: the generalist or specialist approaches.

The first would entail development of UAVs that are capable of performing several different tasks ("Jack-of-all-trades UAVs"). Generalist UAVs would be capable of carrying various interchangeable tools, attached by a universal docking system. The docking system would have to transmit power from the UAV power supply to the attached tool and enable data exchange between the UAV and the tool, so that UAV flight-control systems could maintain stability, in response to the tools' movements or status. A potential disadvantage of this approach might be that human operators would be needed to interchange the attachments and carry out safety tests. Thus, complete autonomy might be sacrificed. However, the generalist approach is likely to be cost-effective, since mass production of the basic UAVs could be performed with economies of scale, whilst design of specialized tools can continue independently, provided a standard docking system is used.

The second approach is to design individual UAVs, each with an integrated tool, to perform one specific task ("specialist UAVs"). This would enable better integration of the tool with the flight systems and remove the possibility of docking-system failure. However, it would be wasteful and therefore more expensive, since drones would be idle when the task, for which they were designed, is not being performed.

Depending on a project's specific needs and constraints, either approach may be appropriate. Labour costs and the costs for developing technologies vary across different parts of the world. Hopefully as the use of UAVs for AFR spreads, the associated costs will come down, as new technologies become more readily available.

Figure 2.6 - A multi-rotor UAV, equipped with a liquid-storage and spraying system (Photo by Stephen Elliott)

Another consideration when using UAVs for AFR is controlling UAV swarms. Performing AFR on areas larger than a few hectares will require co-ordination of multiple drones, perhaps simultaneously performing different tasks, without impinging upon each other's airspace, and without interfering with performance of their programmed tasks. This will require UAVs to communicate with each other, in real time, and adjust their flight paths and operations, in response to the position of every other drone in the area, whilst all UAVs work towards a shared universal objective.

Advances in programming of drone swarms have been considerable in recent years (e.g., ABATTI, 2005; BRUST & STRIMBU, 2016; CONDLIFF 2017; MEHTA 2017; KUMAR 2017), particularly for military purposes, such as intelligence and surveillance (ABATTI, 2005; MEHTA 2017) and for creating spectacular lights shows as large open-air public events. For swarm UAVs, the size of each individual in the swarm is small, and one swarm may consist of 100 of individuals (CONDLIFFE, 2017; MEHTA 2017).

By recognizing various approaches for UAV development, it is important for technologists and forest practitioners to work together at the early stages of development.

CONCLUSION

Restoration of diverse forest ecosystems is one of the most important tasks to mitigate global climate change. In the last few decades, we have gained more knowledge about forest restoration, whilst engineers have also developed UAV technologies, capable of many practical applications relevant to the task. This review has discussed the current use of UAVs in forestry and conservation, and looks forward to greater use of those technologies in forest restoration, gradually achieving increased autonomy, as improved technologies become more readily available and more cost-effective (Table 2.2).

UAV technologies can be applied to all aspects of forest restoration, from project planning to monitoring and assessment of project achievements, in terms of biomass accumulation, recovery of forest structure and biodiversity and the ultimate goal of returning ecological functioning. The time is ripe for a cross-disciplinary effort to develop and implement these technologies. The integration of engineering and restoration ecology is the hope for our future.

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Table 2.2 – Idealized auto-restoration work flow and required technologies, showing how the need for human inputs could potentially be minimized

TECH NEEDED	TASK	OUTPUT
Human intervention	Establish ground station	Power supply, stocks of herbicide & fertilizer
UAVs, cameras, tree-identification software	Survey nearby target forest remnant	Set restoration goals – locate seed sources
UAVs, cameras, restoration planning software	Survey restoration site	Restoration plan – seed requirements calculated
UAVs, seed collection devices & controlling software	Seed collection	Seeds
Human intervention	Process seeds & prepare them for delivery	Seed bombs
UAVs with seed-dropping devices	Aerial seeding	Restoration site seeded with trees
UAVs + spraying devices for herbicide and liquid fertilizer	Maintenance	Tree seedlings protected from weeds and supplied with nutrients
UAVs + cameras, tree identification software – thermal cameras for animals	Monitoring vegetation and animals	Data: tree survival, growth & biomass; recovery of forest structure & faunal recolonization
REPEAT	Move ground station to new restoration site	Restoration objectives achieved

Figure 2.7 - Raw UAV-borne-compact-camera image showing two tree crowns (birch and poplar species) with different spectral signatures (modified from Lisein et al., 2015)

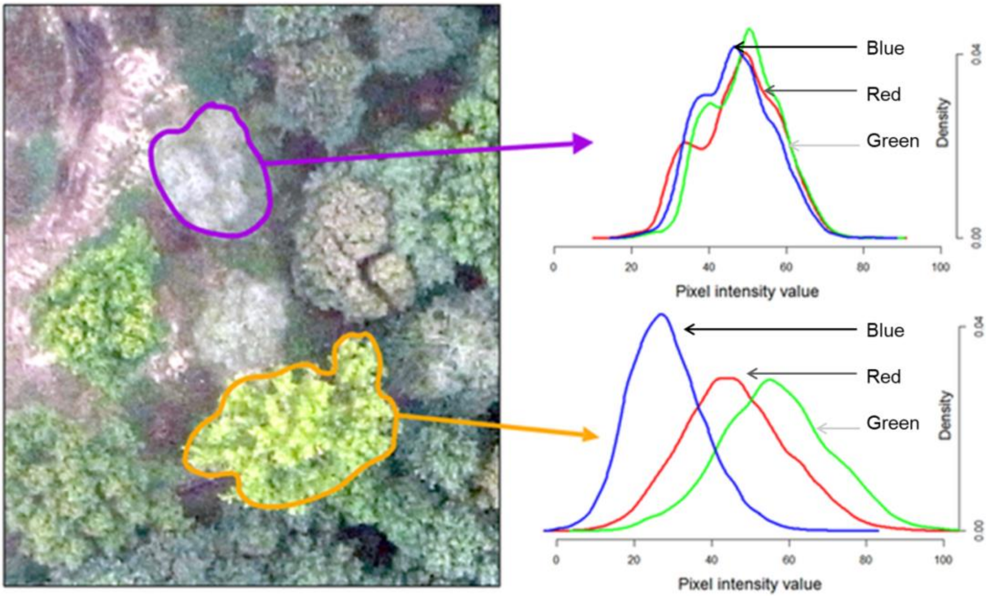

Figure 2.8 Views of the same point from different angles for detecting fallen trees (arrows). Nadir looking image detects three fallen trees hidden by standing trees (boxes) (reprinted from Inoue et al., 2014)

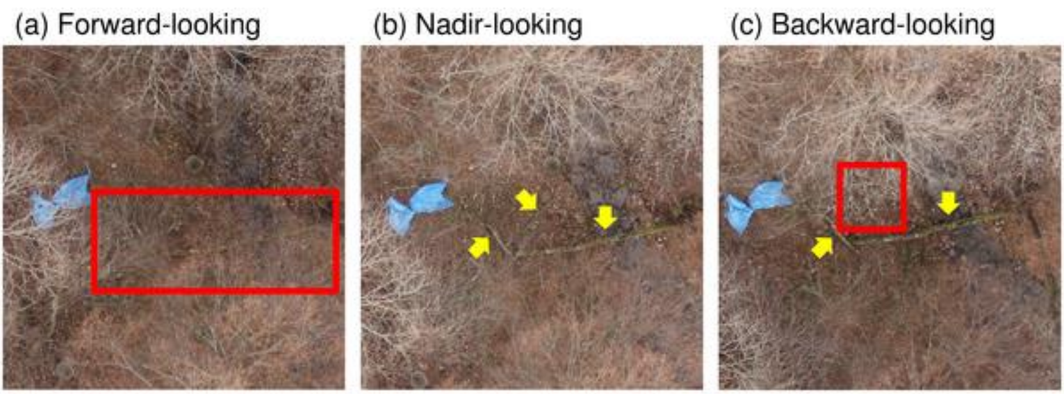

Figure 3.1. Tree crown map produced manually from a high-resolution aerial image of Barro Colorado Island (Panama). Mapped species: *Jacaranda copaia* (A), *Attalea butyraceae* (B), *Tabebuia guayacan* = *Handroanthus guayacan* (C) and *Astrocaryum standleyanum* (D). Photo by Marcos Guerra

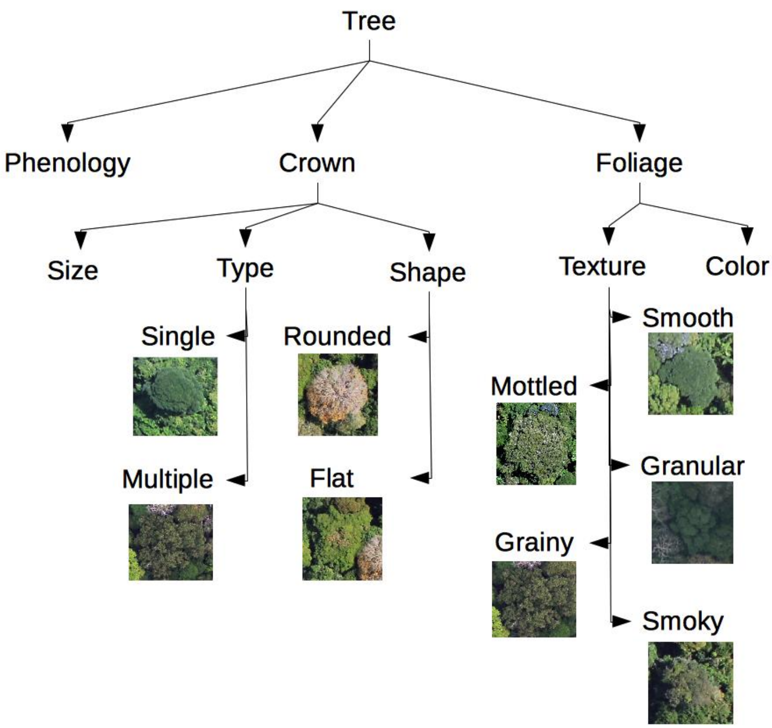

Figure 3.2. Criteria used for manual identification of tree crowns of different species from high-resolution aerial images of Barro Colorado Island (Panama).

Chapter 3

APPLICATIONS OF REMOTE SENSING FOR TROPICAL FOREST RESTORATION: CHALLENGES AND OPPORTUNITIES

Dawn Frame[1] and Carol X. Garzon-Lopez[2]

ABSTRACT

The tremendous physical and material efforts required to accurately assess forest degradation and to plan and monitor vegetation recovery using conventional ground surveys, often limit the success of tropical forest restoration projects. Remote sensing has become an important tool for biodiversity monitoring, ecological studies and climate change assessments. It has enormous potential to automate assessments of forest degradation and to standardize and increase accuracy of information at multiple temporal and spatial scales throughout the forest restoration process. It also drastically reduces labour costs involved in vegetation surveys. Remote sensing data vary in their complexity from two-dimensional RGB images, collected from analogue or digital cameras, to three dimensional hyperspectral cubes, covering hundreds of bands. Here we summarize current applications of available remote sensing methods for various forest restoration tasks and discuss the challenges and opportunities of using remote sensing in automated tropical forest restoration.

Key words: remote sensing, GIS, aerial images, hyperspectral data, lidar, multispectral data, satellite data, tropical tree species identification.

INTRODUCTION

Structurally complex and carbon-rich, tropical moist and wet forests (hereafter, Humid Tropical Forests, HTF) are some of the most biologically diverse ecosystems on Earth. They exhibit high species richness but, at least in the Neotropics, most species are quite rare. TER STEEGE et al. (2013) estimate that 1.4 % of species account for about half of all individuals. As plants are primary producers and dominate landscapes, their roles are always key to habitats. However, tropical forest destruction is on-going. Based on Landsat data, current rates of tropical

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deforestation globally are estimated to be 7.6 million ha per year (ACHARD et al. 2014). Such estimates vary for several reasons, the most important of which are the definition of deforestation (e.g., degree, change or identity of tree canopy cover) and the counting method (e.g., satellite data, field-based extrapolations etc.).

Identifying and locating specific trees, or group of trees, is fundamental to i) assessments of forest biodiversity, ii) increasing our understanding of ecosystem functioning and iii) reforestation methods that prescribe the use of multiple native species to re-establish forest structure (e.g., the framework species method (ELLIOTT et al., 2013). Traditionally, identification and mapping of HTF species has been done using labour-intensive, ground-based surveys or by interpreting large-scale (> 1:4000) aerial photographs (ZHANG et al. 2006). Both methods are costly and time-consuming. However, with the advent of small unmanned aerial vehicles (UAVs), aerial photography has become both more cost-effective and rapid. In addition, researchers are now also turning to other remote sensing methods (Table 3.1) to assess a host of vegetation parameters, such as spatial structure, complexity, dynamics and species distribution.

Aerial digital photography

Maps of species distributions are fundamental to the study of tropical forest ecology, allowing us to increase our understanding of population and community dynamics, and they form the basis of ecological monitoring and management plans (MYERS, 1982; CONDIT et al., 2000; JANSEN et al., 2008; MORGAN et al., 2010).

High-resolution aerial photography is a relatively inexpensive solution for the identification and mapping of species at large scales (Fig. 3.1). It has been applied to the identification of tree species in temperate forest with good results (PAINE & KISER, 2003). In the case of the highly-diverse HTFs, this technique has been used in very few cases because of the difficulty associated with recognizing species from crowns, often intermixed, and has mostly been limited to mapping a single or few, often distinctive, species (Fig. 3.1).

SAYN-WITTGENSTEN (1978) attempted to identify timber tree species in the tropical forests of Surinam and found the approach promising, but highlighted the need for criteria to identify species. Later, CLEMENT & GUELLEC (1974) and VOOREN & OFFERMANS (1985) working in Gabon and south-eastern Ivory Coast, were able to map one focal species in each ecosystem. MYERS (1982) successfully identified 24 tree species with 75% accuracy in the forests of Queensland (Australia).

Table 3.1. Current and planned remote sensing products and platforms with specifications. Number of signs increases with increasing costs ($) or data processing/storage (*) needed.

Platform	Sensor	Resolution (m)	Extent	Frequency (days)	Spectral regions (bands)	Tree species identification	Other applications	Processing/ Storage	Costs
	Ikonos	1-4						**	$$$
	Quickbird	0.65-2.62		3-4	up to 4	Only very conspicuous (color, size) tree species	Tree crown density and size Forest condition	**	$$$
	WorldView2	0.65-2						**	$$$
	GeoEye1	0.65-2						**	$$$
	Landsat 7	15-60		15	8		NDVI Forest type classification	**	$$
Satellite	MODIS	250-1000	>1000 km²	1-2	36	Forest type classification	Tree crown density and size Forest condition	**	$
	Hyperion EO-1	30		15	220		Spectral signature, functional types	***	$$
	EnMAP	30		4	400		Planned for 2018		
	PRISMA	20-30		1-2	10		Planned for 2015		
	HyspIRI			5	10		Planned for 2022		
	Hyperspectral (AVIRIS or APEX)	2-20			224	Identification by spectral signature	Biomass Plant functional traits Invasive species ID, location NDVI	***	$$$$$
Airborne	LiDAR	0.15	<1000 km²	Planned	3D structure	Provides data on height and form, used in combination with other imagery for identification	Canopy height Biomass Digital elevation model Tree crown structure	***	$$$$$
	Aerial images	1-10			up to 3	Identification by tree (mostly crown) morphology	Tree crown size and density Forest status	**	$$

Trichon and colleagues (GONZÁLEZ-OROZCO et al., 2010; TRICHON, 2001; TRICHON & JULIEN, 2006) developed a multi-criteria hierarchical system to describe crown typology from aerial photographs; it comprised seven discrete variables: crown size, phenology, crown type, crown shape, foliage texture and colour (Fig. 3.2). This crown identification key was developed at a study site having precise ground coordinates of previously identified (known) species (GARZON-LOPEZ et al., 2013). The crowns, visible in the aerial images were carefully matched with their ground locations and, in this way, the species were mapped.

The aforementioned method relies on manual interpretation (delineation) of crowns by trained experts, people who are often in short supply and expensive to employ. Consequently, automated interpretation has been attempted (just as for other forms of remote sensing) using modern methods of digital image analysis, based on pixel- or object-based classifications (by a process of segmentation) (MORGAN et al., 2010). In fact, the steps involved, such as associating known crowns with location, using a combination of criteria (involving sun-lit pixels and e.g., image texture and shape recognition) are roughly similar in manual and automated interpretation of tree crowns.

Some of the applications of aerial tree crown interpretation include assessment of tree aging (VOOREN & OFFERMANS, 1985) and crown dynamics (HERWITZ et al., 1998); monitoring of forest degradation or fires (PANEQUE-GÁLVEZ et al., 2014); locating fruiting events and measuring their intensity (JANSEN et al., 2008; VAN ANDEL et al. 2015); and the development of large-scale species distribution maps, to study plant-habitat associations (GARZON-LOPEZ et al., 2014), animal behaviour (BROWN et al., 2014) and animal movement patterns (CAILLAUD et al., 2010; VAN ANDEL et al., 2015).

The choice of a platform, used to carry the camera, depends on the extent of the study area and platform availability, and has a significant effect on determining project costs. Platforms have typically been (in order of increasing cost) ultra-light aircraft, small airplanes and helicopters. With the advent of inexpensive off-the-shelf and do-it-yourself UAVs, user-friendly, readily mobilized platforms are now available, allowing exceptionally cost-effective forest mapping. Flight patterns for UAVs, carrying small-format cameras, can be pre-programmed to capture aerial photographs (images) with a high degree of overlap for later mosaicking. Furthermore, using off-the-shelf automated photogrammetric software packages, such images can be used to generate digital elevation models (DEMs). Thus, the canopy can be mapped and a digital terrain model (DTM) produced at resolutions, set by the user. Additionally, UAV missions may be run and operated by trained local people, so that images may be obtained in remote areas without entailing numerous lengthy field trips by foresters or other expensive specialists. Depending upon regional expertise, aim of the aerial survey and computer processing power available, crown identification can be done i) manually, ii) using a combination of experts and trained volunteers (González-Orozco et al., 2010) or iii) by automated digital image analysis, developed and run by experts.

In conclusion, aerial images can be used to support various forest restoration tasks (Table 3.2), from rapid pre-intervention site assessments for determining baseline levels of degradation, and identification (and location) of trees that can serve as seed sources, to monitoring of the progress of restoration following interventions.

Light Detection and Ranging (Lidar)

Lidar technology measures the travel time of a laser pulse from an emitter to a target and back to a detector (up to 400,000 pulses of light per second) and derives the distance to the target from the return time. When using a lidar unit mounted on an aerial platform (AP) to survey vegetation, pulses are reflected from the canopy (first return) and the ground (last return). Canopy height is calculated by subtracting the first from the last return time, taking into account AP position (altitude, yaw, roll and pitch). Using this approach, the instrument collects three-dimensional data in large volumes, at high density and with unprecedented precision.

The instrument consists of a laser emitter, a global positioning system (GPS) receiver, providing geographic location, and an inertial measurement unit (IMU), which records AP position. Lidar systems are categorized according to the type of data they record, as either discrete return or full waveform systems. Discrete return systems can be programmed to record (i) only the first return, (ii) the first and last return; or (iii) multiple returns; full waveform systems transmit continuous signals and the distance is measured based on changes in laser intensity.

Data resolution is dependent on the number of pulses per unit area and the size of the pulse (area of the footprint), which is in turn determine by altitude. For the discrete system, the footprint varies between 0.2 and 0.9 meters, while in full waveform systems it varies between 8 to 70 meters (Lim et al., 2003). Full waveform systems are gaining popularity because they can capture reflections of the emitted laser pulse in greater detail than discrete ones.

Aerial lidar sensors deliver a 3D point cloud of the forest that can then be processed to i) a digital surface model (DSM) that includes all the objects on the ground (e.g., trees, buildings, etc.), ii) a digital terrain model (DTM) that provides a view of the bare ground (without any objects) and iii) a set of very precise canopy metrics like the canopy height model (CHM), a canopy density map and the average, maximum and minimum canopy height. These forest height metrics can be related to observed above ground biomass (AGB) estimated by field measures and allometric relationships in inventory plots. Operational costs often limit the spatial extent of lidar-derived AGB estimates, but accurate estimates are vital if forest restoration projects are to be funded by REDD+ (Reducing Emissions from Deforestation and Forest Degradation) or other carbon-trading systems. In combination with other remote sensing approaches, local AGB maps may be scaled up to cover larger areas (LAURIN et al., 2014).

Up-scaling an aligned lidar sampling of Panama using Landsat satellite data of topography, precipitation and vegetation cover, ASNER et al. (2013) modelled carbon stocks at a 1 ha spatial resolution to produce a carbon map of Panama. They found that lidar estimated carbon stocks were similar to those estimated from inventory plots and concluded that lidar collected measurements can replace laborious field-derived ones, although validation plots "remain highly valuable for increasing accuracy and transparency" (ASNER et al., 2013). Using a light airplane equipped with a small footprint lidar, hyperspectral sensor and a digital camera for aerial photographs, LAURIN et al. (2014) estimated AGB of forest in the Gola Rainforest National Park in Sierra Leone. These workers found that integration of the hyperspectral data improved the lidar-based model and cautioned that high quality field data is essential for lidar-based AGB estimates, particularly if the estimates from airborne lidar are to be used to upscale the field-measurements.

Even though lidar data acquisition and processing can be very expensive (HUMMEL et al., 2011), there is an economy-of-scale effect whereby the larger the study area, the greater the lidar data acquisition costs are reduced, in the case of Panama to about $1.00 USD per hectare (ASNER et al., 2013). While, ground field plots are expensive to establish and maintain, costing on the order of (~$2000 to $5000 USD per ha) for the same country (ASNER et al., 2013).

Notwithstanding, on the whole, prices for aerial lidar measurements are decreasing as lidar sensors become smaller, lighter and cheaper, as computer processing power and data transfer rates increase. Further, lidar efficacy is improved when used in combination with other technologies. For example, in automated aerial tree mapping, both lidar and hyperspectral data can be collected simultaneously (BALDECK et al., 2015). Lidar data are used to derive tree height measurements and the 3D structure of the vegetation and are also used for accurate orthorectification of the spectral data. Medium-priced systems that combine very high-resolution photography with lidar are also available. In Cambodia, SINGH et al., (2015) used such a system for tree mapping in HTF, where ground field data collection was not possible due to the presence of landmines.

Imaging spectroscopy (spectroradiometry)

Spectroscopy is the analysis of light, emitted by or reflected from matter and its variation in energy at different wavelengths. In reflected-light spectroscopy, the basic property of interest is spectral reflectance: the ratio of reflected energy to incident energy, as a function of wavelength. For most materials, reflectance varies with wavelength, because energy at different wavelengths is differentially scattered or absorbed. These variations in reflectance are evident, when spectral reflectance curves for different materials, in our case vegetation, are compared. Pronounced downward deflections of the curves indicate wavelengths that a material selectively absorbs and are termed "absorption bands". Overall spectral curve shape, and absorption bands' strength and position of absorption bands can be used to identify, and discriminate among, different materials. Minerals, which are comparatively structurally simple and stable, can be classified in this manner and a library of reflectance spectra exists. Vegetations and their component plants are dynamic and interpretation of their reflectance spectra is more complex. In a general manner, spectral reflectance curves of healthy plants have characteristic shapes, related to plant attributes. In the visual spectrum (VIS), curve shape is governed by plant pigment (e.g., chlorophylls, carotenes, anthocyanin, betalains) absorption. Chlorophylls absorb blue and red wavelengths more strongly than green, which is largely reflected (hence plants appear green to our eyes). This appears on reflectance curves as a characteristic peak within the green wavelength range. Reflectance rises sharply to values of about 40 – 50% for most plants across the boundary between the red and near-infrared (NIR) wavelengths (680 – 750 nm), and is known as the "red edge" effect. This high NIR is related to several factors such as chlorophyll concentration, species morphology (organization and construction), developmental stage and leaf water content (GHIYAMAT & SHAFRI, 2010). Otherwise, in the NIR, most of the remaining energy is transmitted and can interact with other lower leaves. Beyond 1.3 µm, reflectance decreases with increasing wavelength, except for two conspicuous water absorption bands, near 1.4 and 1.9 µm (SOLDOVIERI et al., 2011). Imaging spectroscopy is typically studied between 400 and 2500 nm, that is from the VIS 400-700 nm, through the NIR 701 – 1400 nm and Short-Wave InfraRed 1 (SWIR 1) 1401 - 1900, to the Short-Wave InfraRed 2 (SWIR2) 1901 – 2500 nm.

Although terminology is imprecise, a general distinction is made between multispectral and hyperspectral sensors. Multispectral remote sensors (such as the Landsat Thematic Mapper and SPOT XS) produce images having few relatively broad wavelength bands, whereas hyperspectral remote sensors collect image data simultaneously in dozens or hundreds of narrow, adjacent spectral bands.

Hyperspectral measurements make it possible to produce a continuous spectrum for each image cell or pixel. These data sets are generally composed of about 100 to 200 spectral bands of relatively narrow bandwidths (5-10 nm), whereas multispectral data sets are usually composed of about 5 to 10 bands of relatively large bandwidths (70-400 nm). Hyperspectral imagery measurements can be represented as a data cube, with spatial information represented by the X-Y plane and spectral information represented in the Z-direction (Fig. 3.4). Multispectral sensors, principally deployed on satellites, are useful in detecting vegetation types but have limited capacity to detect tree species (especially tropical ones), because they lack the fine spectral resolution provided by hyperspectral sensors (CASTRO-ESAU & KALACSKA, 2008). Recall that resolution has two components, a spatial one and a spectral one. In hyperspectral imagery, reflectance spectra are continuous and pixel resolution is in the order of 15 cm to 1 m, depending on the sensor and its distance from the target.

The potential uses of hyperspectral imagery (in the lab or airborne, often in combination with other remote sensing techniques) for monitoring HTF composition, cover and function are numerous and the subject is vast. Hyperspectral data (spectral signatures) are essentially a reflection of interactions between light and physical and chemical properties, be they cells, tissues, organs (often leaves, known as leaf optical properties), individuals (often crowns), populations, communities, ecosystems or other higher-level groups. Hence, some of the common data uses are for studies of:

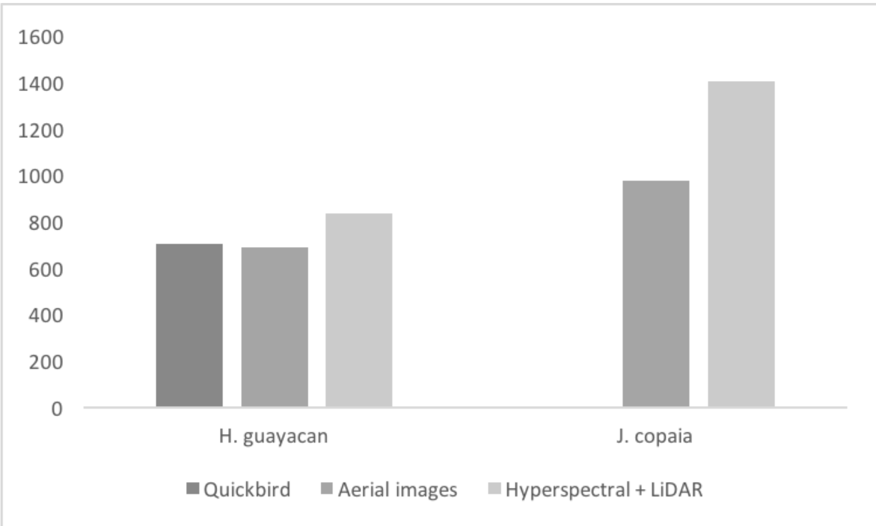
1. leaf chemistry, structure and function (e.g., rates of photosynthesis);
2. life forms (e.g., liana or tree, see KALACSKA et al., 2007);
3. phenology and
4. detection and mapping of species.

Moreover, combinations and derivatives of the elemental data are the building blocks for detection/analysis of plant traits and growth forms (HOMOLOVÀ et al., 2013), and vegetation indices (LAURIN et al., 2014). Currently the use of hyperspectral sensors is largely limited by the costs of the sensor as well as associated data acquisition and processing, but this is rapidly changing with the development of new technologies, such as compact light-weight sensors and open-source processing software.

APPLICATIONS OF REMOTE SENSING TO TROPICAL FOREST RESTORATION

Remote sensing technologies have a wide range of applications in forest restoration, from the identification and assessment of sites to be restored, identification of tree species, location of "mother" trees as seed sources and the necessary frequent monitoring of the restoration process. Multiple technologies can be combined to increase the efficacy of restoration, while minimizing limiting factors to restoration such as costs, labour and time. They also enable restoration to be carried out on remote, inhospitable terrain, where it would otherwise be impractical because of the aforementioned limitations.

Figure 3.3. Number of tree individuals, in the tropical forest of Barro Colorado Island (Panama), identified using satellite (Quickbird), aerial and hyperspectral combined with lidar images, respectively (adapted from Baldeck et al., 2015).



BALDECK et al. (2015) recently presented an automated method to identify tree species in HTF using combined hyperspectral imagery and lidar data. These authors compared their results with two previous attempts made at the same study site using satellite-based Quickbird images and automated crown delineation methods (*Handroanthus guayacan* and *Jacaranda copaia*), and manually delineated crowns of high-resolution aerial images (*J. copaia*). They found that hyperspectral + lidar data resulted in better species detection, due to higher resolution of forest structure (Fig. 3.3), however, their method is considerably costlier.

Remote sensing method of choice will differ depending on goals, budget and the landscape. For example, initial assessment of the landscape might require information at low resolution over a large area, for which the best approach might be free, readily-available, on-line, pre-processed satellite images. However, if the aim is to assess forest structure and locate and identify seed trees, then the best option might be aerial images (approx. $0.2 USD per hectare), or if it is to characterize (and monitor changes in) forest structure (e.g., canopy height, AGB, functional diversity) or develop a high-resolution DEM the best results will be obtained using hyperspectral +/- lidar sensors (approx. $0.5 USD per hectare). The selection will also depend on the characteristics of the focal species (Fig. 3.2) and the selected area (Table 3.2).

DEVELOPING PRACTICAL APPLICATIONS TO AUTOMATE FOREST RESTORATION

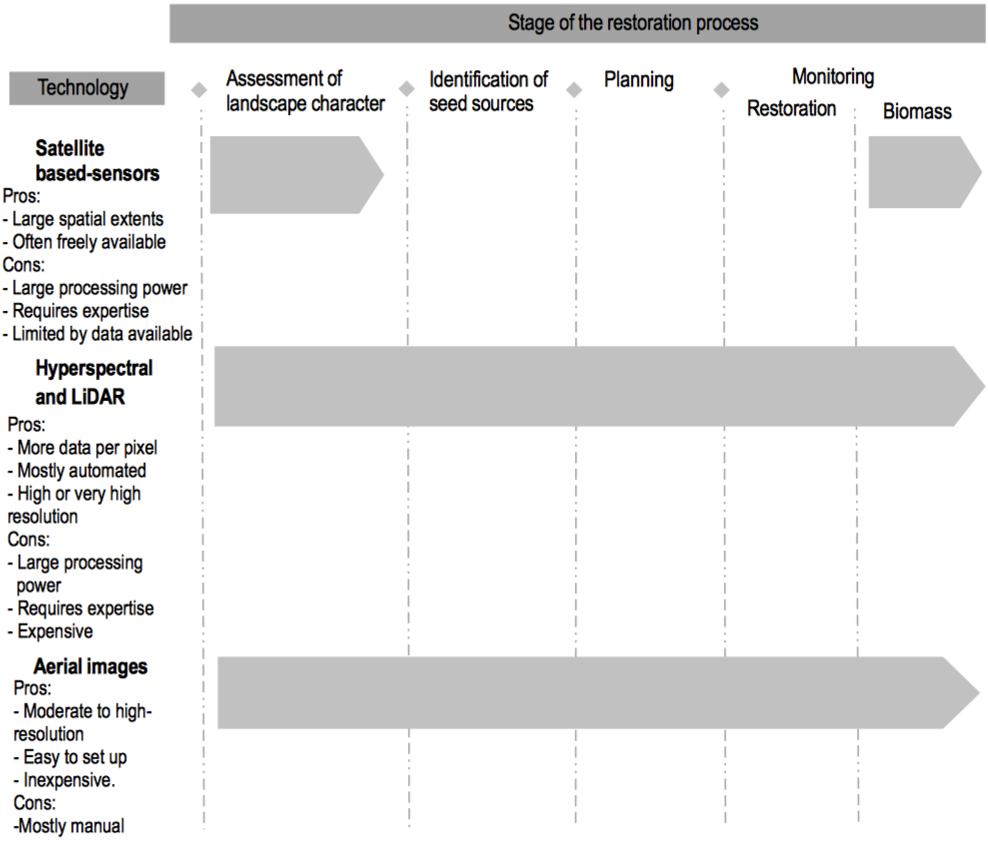
We turn our attention now to the priorities for research and development that arose out of the brainstorming sessions of the 2015 workshop on Automated Forest Restoration (AFR) Chiang Mai, Thailand – how to apply the imaging technologies described above to develop robust, cost-effective and automated methods for forest restoration.

Firstly, it must be emphasized that basic knowledge about how to restore local forest ecosystems, by conventional means, must already exist, before technology can be used to make the tasks of forest restoration easier. Restoration sites should be selected on the basis of sound social and ecological criteria, through consultation with all stakeholders; a process for which there is no technological substitute. A list of indigenous forest tree species known to be most suited to the conditions at the restoration site is also an essential minimum pre-requisite.

The next step is to map the selected restoration site, locate the nearest surviving remnant of the reference (or target) forest ecosystem (which will serve as the goal of restoration) and locate individual seed trees of the selected, suitable, species within it.

This can be done in several ways and at multiple scales (it is advisable to use more than one). At large scales, freely-available satellite images can be used. At local scales, numerous points can be verified by using hand-held GPS receivers, or UAV-mounted GPS receivers and cameras (as described above). The latter method could also generate DEMs and CHMs.

Table 3.2. Applications of remote sensing to various stages of tropical forest restoration.



Another early important step can be to develop databases that combine information gleaned from previous experience and to fill knowledge gaps. The databases should cover species location, phenology (flowering, fruiting, leafing months), reproductive biology, seed dispersal method, seed germination requirements and seedling biology. The database should be linked to an image library. This library should contain different views of trees (e.g., crowns, trunk) and various organs, as well as of seedlings and treelets; priority should be given to framework species. UAV-mounted cameras may be used to obtain some of these images. The image library would form the basis for a species-identification tool, similar in concept to Pl@ntNet (JOLY et al., 2014) (see Chapter 11).

After these steps, if higher resolution is required then hyperspectral and lidar sensors may be employed. As these sensors are becoming smaller, lighter and less expensive, by the time the databases and image libraries near completion, complementary new technologies (such as the promising hyperspectral camera based on CMOS technology) and user-friendly methods are likely to have become widely available.

Currently, challenges to acquiring aerial images from UAVs, and/or to data acquisition from UAVs, airplanes and satellites include:

1. Most hyperspectral and lidar sensors are expensive and heavy (> 4 kg). Although changing, this remains an important limitation. Moderately priced UAVs have a maximum payload capacity of ca. 2-4 kg and limited flight durations (30-60 mins), depending on weight.
2. High dimensionality of the data makes both lidar and spectroscopic (especially hyperspectral) imagery hard to transfer and store. High-performance computers, having large storage capacities, are necessary. Moreover, modelling algorithms are complex and require long computational times;
3. Most HTF tree species are very rare, even over large spatial scales.
4. Airborne and satellite spectroscopic sensors detect over-storey trees. Understory trees cannot be detected by these means.
5. When using lidar, dense canopy cover limits the number of discrete pulse returns from the ground, making it difficult to produce well-resolved DTMs.
6. Weather conditions affect remote sensor outputs. Clouds can block satellite images. Flights must be conducted on clear days or below clouds and in little to no wind. High humidity can also affect results.

Although numerous challenges remain to be surmounted before many recently described methods of remote sensing can be practically applied to the automating of tropical forest restoration, the technologies outlined in this article also open up many new opportunities. Using inexpensive digital cameras mounted on cheap off-the-shelf or do-it-yourself UAVs (such as the Flone described in Chapter 7) is an excellent starting point for providing basic information, for planning and implementing successful restoration projects, as well as providing a means of monitoring on-going projects.

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KEY TO ABBREVIATIONS

AFR = Automated Forest Restoration
AGB = Above Ground Biomass
AP = Aerial Platform
CHM = Canopy Height Model
DEM = Digital Elevation Model
DSM = Digital Surface Model
DTM = Digital Terrain Model
HTF = Humid Tropical Forest
Lidar = Light Detection and Ranging
NIR = Near InfraRed
NDVI = Normalized Difference Vegetation Index
SWIR = Short Wave InfraRed
UAV = Unmanned Aerial Vehicle
VIS = Visual (spectrum)

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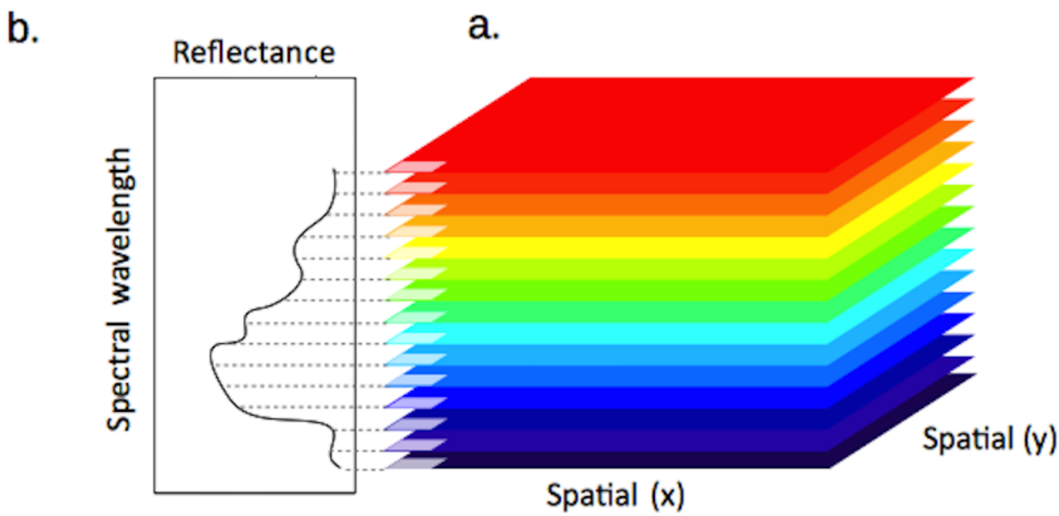

Figure 3.4. a. The Hyperspectral image cube is built as the sensor passes over the ground. b. The hyperspectral curves are generated from the reflectance values extracted from a specific point/area/pixel (x, y) at each wavelength

Figure 4.1 - Different stages of degradation/regeneration/succession of native forest

Chapter 4

AUTOMATING SITE ASSESSMENTS USING DATA FROM UAVS

Alejandro Miranda[1,2], German Catalán[1], Adison Altamirano[1] and Manuel Cavieres[1]

ABSTRACT

Much progress has been made in remotely detecting forest loss, particularly by using satellite imagery. However, quantification of different stages of forest degradation continues to be challenging. Compared with satellites, UAVs (or drones) can deliver images of much higher spatial resolution and enable estimation of forest characteristics with greater accuracy. Hence, such data from UAVs may enable the quantification of different levels of forest degradation in greater detail than ever before.

In this paper, we discuss the potential of data from UAVs to i) assess forest degradation at the site level, ii) determine the conditions of reference (or target) forest ecosystems and iii) detect the extent of forest regeneration. Additionally, we quantify and compare several forest stand-level variables, measured in the field (observed) and from UAVs (detected) in a Chilean temperate forest.

Detected values from UAV data were 27-100% of the observed values for species richness, 25-61% for counts of trees and 67-81% for basal areas. Observed vs detected basal area measurements were highly correlated (R^2=0.9). Results, using a canopy structure metric, to predict tree species richness (R^2=0.42) and number of trees (R^2=0.45), were promising.

We conclude that data from UAVs may be useful to detect gradients in vegetation structure, to determine degradation stages of restoration sites and consequently, to establish restoration goals and thus derive the most appropriate methods to achieve them.

Key words: forest degradation, remote sensing, canopy structure.

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WHAT IS A PRE-RESTORATION ASSESSMENT?
WHY IS IT IMPORTANT?

The three main stages of restoration projects are: i) planning, ii) implementation and iii) evaluation. Planning establishes project aims and how to achieve them. HOLL & AIDE (2011) wrote that restoration strategies must be decided on a site-by-site basis. They should consider ecosystem resilience (or the intrinsic recovery rate), degradation levels (or land-use history) and landscape context (or surrounding matrix), as determined by a pre-restoration site assessment. Conducting these analyses prior to selecting restoration approaches should result in efficient use of restoration resources and should maximize the chances of success (HOLL & AIDE 2011).

A pre-restoration site assessment serves several purposes. It quantifies the current degradation stage of the ecosystem and provides a baseline, against which changes due to restoration can be evaluated. It also defines the extent and existing potential of natural forest regeneration and identifies barriers to its progression (ELLIOTT et al., 2013). Thus, site assessments guide restoration, by helping to determine the location and intensity of restoration actions across sites.

The degradation stage of an ecosystem is determined by comparing it to a reference ecosystem (also known as target ecosystem). Observations of a reference ecosystem help to define the levels of ecological attributes (e.g., biomass, structure, biodiversity etc.) aimed for by restoration. The attributes, assessed in a reference ecosystem, can include: species composition, community structure, abiotic conditions, exchanges of organisms and materials with the surrounding landscape and anthropogenic influences. The attributes that are measured depend on the restoration aims, but the same attributes should be assessed when describing both the reference ecosystem and the state of degradation in pre-restoration site assessments (Fig. 4.1). For example, ELLIOTT et al. (2013) defined five levels of tropical forest degradation, distinguishing each by critical thresholds that, once crossed, require major shifts in restoration approach.

The collection of such biophysical information during pre-restoration site assessments allows the identification of methods to re-initiate or accelerate those ecological processes that have been arrested or retarded. Thorough assessments of both the degraded and reference ecosystems are therefore essential for planning effective restoration strategies.

All the ecological indicators, suggested by ELLIOTT et al. (2013) to define degradation stages, can be quantified in the field with a pre-restoration site assessment. However, this requires a large field effort. Instead, we can measure these (or other) attributes using UAVs, to differentiate degradation stages, and to define the reference ecosystem for auto-site assessment in large and remote areas for the whole site.

The approaches of ELLIOTT et al. (2013) and HOLL & AIDE (2011) emphasize the important role of pre-restoration site assessments. Three levels of information are needed: i) landscape or land cover, including landscape structure and composition of the site and surrounding matrix and spatial relationships among landscape elements; ii) vegetation structure, including species composition, diversity, density, size and spatial distribution of adult trees and iii) forest regeneration, including the size and spatial distribution of natural regenerants.

At the landscape level, quantifying forest loss has progressed greatly, since the development of remote sensing by satellites. Distinguishing between native forest and other forms of land cover (e.g., pasture, exotic forest plantations, crops etc.) is relatively easy. However, quantifying different degradation stages, within native forest is more difficult, since logging, fires and cattle browsing cause different qualitative changes in forest structure and composition, which are difficult to distinguish.

Quantifying structural changes within forests is more challenging than measuring wholesale forest loss and requires images with high spatial resolution, to distinguish among tree species. For example, in the Barro Colorado (Panama) tropical forest, GARZÓN-LOPEZ et al. (2013) achieved high accuracy of species identification, using aerial photographs with 8.5 cm spatial resolution, clearly demonstrating the usefulness of very high-resolution images for forest surveys and highlighting the need to complement the high spectral resolution of satellite images over large scales with more detailed imagery at closer quarters.

Quantifying forest regeneration presents a major challenge, due to: (i) the small size of regenerants (e.g., tree seedling or sapling or tree stumps) and (ii) the fact that they may be hidden beneath a canopy of herbaceous weeds. Even using very high-resolution images over open spaces, counting small seedlings, is difficult let alone identifying them. These tasks become even more challenging when regenerants are hidden beneath a canopy of trees (such as in stage-1 degradation) or where the cover of herbaceous weeds is dense. UAV-mounted lidar technology opens up the possibility of obtaining below-canopy measurements from flying above the canopy or between the trees inside the forest CHISHOLM et al. (2013) (see Chapter 12). Another promising technology, which could be used to assess forest regeneration, is "structure from motion" (SfM) algorithms that create 3D surface models, using RGB images, taken with UAV-mounted digital cameras (ZAHAWI et al. 2015). Such technology is used to construct point clouds of forest structure similar to those that are created by lidar, including canopy height models and roughness metrics (DANDOIS & ELLIS 2013).

HOW CAN DATA FROM UAV HELP WITH SITE ASSESSMENTS?

Various UAV platforms can be used for pre-restoration site assessments. Principle differentiating characteristics include aerodynamic profile, endurance, maximum range, flying time and altitude (SALAMI et al., 2014). The remote sensors that can be mounted on UAVs also vary. Some record images passively (e.g., regular digital cameras) or actively by emitting their own energy (e.g., lidar). Regular visible multispectral cameras (including the infrared band) are the most common sensors currently used with UAVs, but promising trials have been conducted with hyperspectral sensors, lidar and thermal cameras (ZARCO-TEJADA et al., 2012; CHISHOLM et al., 2013; GARZÓN-LOPEZ et al., 2013, SALAMI et al., 2014)

The selection of both UAV type and remote sensor depends on project objectives. Practitioners should choose a platform that is not only capable of achieving project goals, but one that is also labour- and cost-effective. Selection of appropriate technologies depends on the size of the restoration area, budget limitations, the detail and accuracy needed for the project and the costs of geo-referencing, orthorectification and image processing. With larger sites, UAVs become less cost-effective platforms for sensors compared with aircraft or satellites, although UAVs are nearly always more flexible in their use and can achieve high spatial resolution and precision, by flying closer to the vegetation (MATESE et al., 2015).

According to ELLIOTT et al. (2013), pre-restoration site assessments require the measurement of different landscape, diversity and regeneration variables. How much of this information can we get from a UAV? Using a regular RGB camera, mounted on a UAV, three different types of data can be generated a) very high-resolution and geo-referenced RGB mosaic images; b) very high-resolution surface elevation models and c) point clouds of surface elevation from different viewpoints. RGB mosaics and elevation raster data can have a spatial resolution ranging from 5 to 20 cm, depending on flight altitude and sensor type (Fig. 4.3 and 4.4). From the point cloud data (c) (Fig. 4.5) we can estimate an important number of surface properties, similar to those estimated by lidar, such as canopy structure and roughness (ZAHAWI et al., 2015). All this data can be combined to generate useful inputs for site assessments and the drafting of project plans, although different levels of information need different approaches (Table 4.1). An important issue for future UAV research is: what is the minimum information, needed to generate effective restoration plans.

USING REGULAR CAMERAS FOR SITE ASSESSMENTS: AN EXAMPLE FROM SOME TEMPERATE FORESTS OF CHILE

To test some of the technologies described above, we evaluated the capability of RGB images from UAVs, to quantify different stand-level variables in old growth and secondary forests in Araucanía region. In this study, tree plots of 45x45 m were established in each forest type All trees >5 cm DBH were identified and mapped, using a Cartesian system, defined in the field, and recognized in a very-high-spatial-resolution RGB image. The image was captured using a Bormatec Maja fixed-wing airframe, equipped with an APM 2 and Canon S100, flying 100 m above the forest.

We compared field data with those derived from UAV imagery: tree species richness, number of trees and basal area. We also related a canopy structure metric (standard deviation of tree height), calculated from a very-high-resolution surface-elevation model for each plot, with tree species richness and number of trees.

Detected values from the UAV imagery were 27-100% of the observed values for species richness, 25-61% for counts of trees and 67-81% for basal areas (Fig. 4.2). Observed vs detected basal area measurements were highly correlated (R^2=0.9). Use of the canopy structure metric to predict tree species richness (R^2=0.42) and number of trees (R^2=0.45), was promising, but less conclusive.

These preliminary results allow us to infer that data from RBG cameras, mounted on UAVs, may be useful for detecting gradients in vegetation structure, for pre- and post-restoration surveys and monitoring and to establish restoration targets from reference ecosystems.

Table 4.1 – The pros and cons of using UAVs to measure variables used for pre-restoration site surveys (ELLIOTT et al, 2013)

LANDSCAPE	
Intact forest	Easy to detect different land cover types (Fig. 1), but more difficult to determine degradation levels of different forest landscape patches. Distance from remnant forest (seed sources) to restoration sites easily determined.
Herb cover	Can be distinguished, by combining spectral data from herb canopy with digital surface models (e.g., ZAHAWI et al., 2015).
VEGETATION STRUCTURE	
Big Trees	Delineation of individual tree crowns can be done using segmentation imaging techniques: combining spectral information and digital surface models. Crown projected areas and volumes can be calculated – especially for dominant and emergent trees.
Dominant species	Using images with 7-cm spatial resolution, 1 m^2 objects can be detected in forest (GETZIN et al., 2014). Pixel-based species classification is more difficult, because of wide spectral variability in very high-resolution images. Following segmentation, crown texture of individual trees can be quantified. Variability in lighting (e.g., time of day, cloud cover etc.) can change spectral information of the same species across large mosaics.
Richness	For determining canopy species richness, the same approach as used for dominant species can be applied. For the under-storey, it is possible to use different canopy metrics to estimate florist diversity, combining the various data obtained with UAV (very-high-resolution images, surface model and point clouds (ZAHAWI et al., 2015). For example, GETZIN et al. (2012) found that plant diversity was correlated with gap-shape metrics.
REGENERATION	
Regenerants, seedlings, saplings & live tree stumps	Using UAV imagery and sensors to determine regeneration is challenging. Only lidar can be used to directly measure under-storey properties. In closed forest, an approach similar to that of GETZIN et al. (2012) can be used. Another option is to carry out direct UAV measurements by flying below the forest canopy (CHISHOLM et al., 2013) (Chapter 12). In open spaces, VEPAKOMMA et al. (2015) counted individual regenerants fairly accurately using an algorithm to distinguish trees.

Figure 4.2 - Comparison between field data versus data derived from UAV imagery. The whole bar represents the value measured in the field, whereas the grey portion of each bar is the value detected by the UAV-mounted sensor in six different plots.

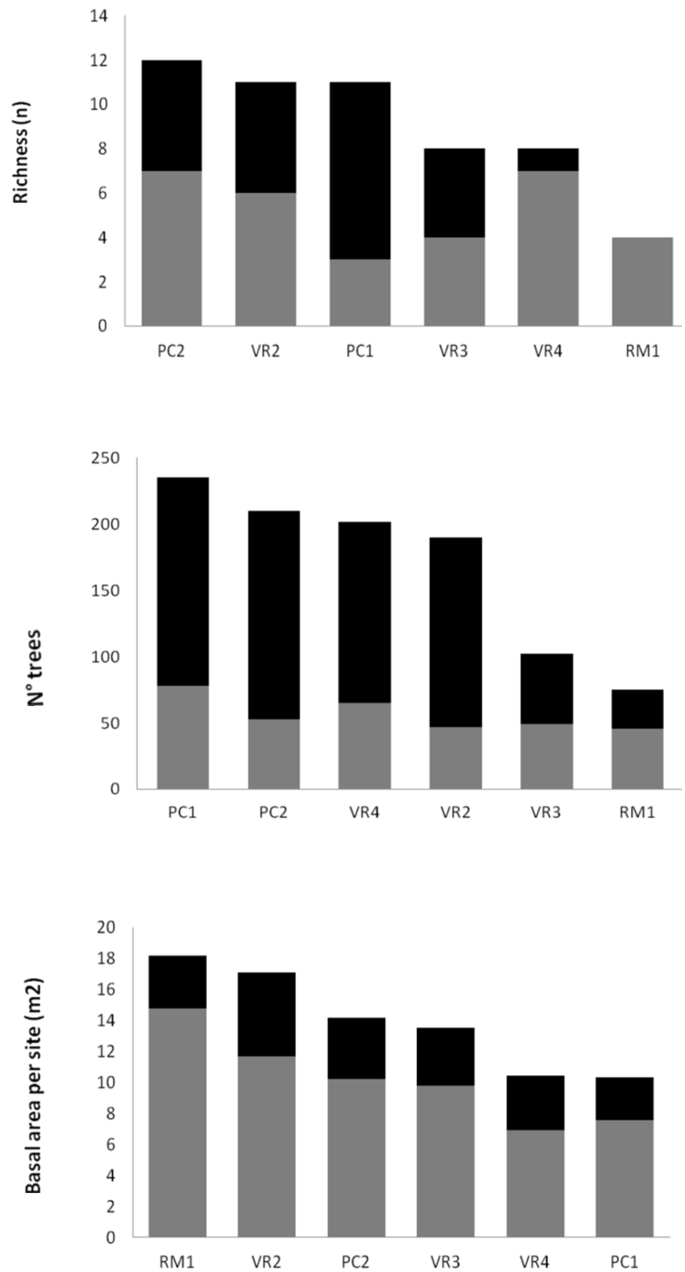

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Figure 4.3 - Very high spatial resolution image of a forest stand

Figure 4.4 – A very high spatial resolution digital canopy surface model of a forest stand

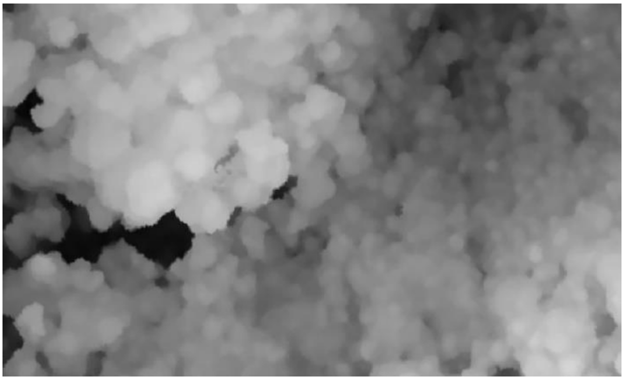

Figure 4.5 – A point cloud of a forest stand

Figure 5.1 - Direct seeding in an abandoned site in Nakhon Si Thammarat, southern Thailand.

Figure 5.2 - A young seedling, two months after direct seeding.

Figure 5.3 - Saplings, 18 months after direct seeding.

Chapter 5

DEVELOPING AERIAL SEEDING BY UAVS: LESSONS FROM DIRECT SEEDING

Dia Panitnard Shannon[1] and Stephen Elliott[1]

ABSTRACT

Direct seeding means sowing the seeds of forest tree species directly into the substrate of restoration sites. It is cheaper than conventional tree planting, but seed predation is high and germination rates low, although various seed treatments and site management can reduce these limitations. Many of the species choices and seed treatments, developed for direct seeding, could be applied to aerial seeding by drones. Successful direct seedling depends on: i) site and species selection, ii) seed supply and quality, iii) site preparation, iv) sowing method and v) post-sowing management. Species/site matching systems are often contradictory or unreliable, so experimentation with species and subsequent monitoring are recommended. Seed supply will limit drone-seeding unless effective seed storage systems can be devised. Seed collection should aim to encompass as much genetic diversity as possible. Recalcitrant seeds must be sown at time of collection, but orthodox seeds can be sown at any time of year (if stored under appropriate conditions). Weeding is often, but not always, essential to the success of direct seeding. When extending direct seeding to drone-seeding, additional factors to consider include seed projectile design, achieving seed burial, optimum spacing between seeds and, perhaps the greatest challenge; automating weed control.

INTRODUCTION

As a tool for forest restoration, direct seeding means sowing the seeds of forest tree species directly into the substrate of restoration sites, usually by hand. Depending on site conditions and methods employed, it can have impressive results Figs 5.1 to 5.4). It is also cheaper than conventional tree planting, since no tree nursery is needed to produce the planting stock (TUNJAI & ELLIOTT, 2012), but it also has several disadvantages, particularly in the tropics.

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Firstly, seed predation in open deforested sites can be very high (HAU, 1997). Secondly, germination rates can be very low, due to desiccation in exposed sites and the mortality rates of seedlings, growing from seeds in the field, is usually much higher than those of planted tree saplings, since the young, tiny, seedlings that emerge from seeds are far more vulnerable to climatic extremes, diseases, grazing animals and attacking insects than nursery-raised tree saplings are (TUNJAI, 2011). In nature, only a very tiny proportion of seeds, dispersed into deforested sites, germinate and the seedlings that grow from them have an extremely low probability of growing into mature trees. Therefore, direct seeding usually also involves treating seeds or protecting them and the resultant seedlings from competition or desiccation, by applying hydrogels and/or chemicals (e.g., germination enhancers or predator repellents), to increase establishment rates above those that can be expected of naturally-dispersed seeds (see Chapter 8).

The cost savings of replacing conventional tree planting with direct seeding range from 30% to 90% (ENGEL & PARROTTA, 2001; TUNJAI, 2011), although in a survey of 120 papers on the subject, PALMA & LAURANCE (2015) reported that the average percentage survival of direct-seeded seedlings was only 18%: three times lower than that of nursery-grown planting stock (62%), but considerably higher than that of naturally dispersed seeds.

Aerial seeding is a logical extension of direct seeding. It can be useful where direct seeding must be applied to very large areas, for restoring steep, inaccessible sites, or where labour is in short supply. Many of the same species choices and seed treatments, developed for direct seeding, can be applied to aerial seeding equally well. China leads the way with this technology; having carried out dozens of research programs on aerial seeding since the 1980's and applied the method to millions of hectares, to establish plantations of mostly conifers and to reverse desertification. Whilst aerial seeding can seed vast areas rapidly, it is also expensive. Aircraft are expensive to buy or maintain. They require the use of airports and trained pilots and have a large carbon footprint – not ideal when try to promote forest restoration for carbon sequestration (ELLIOTT et al., 2013).

Therefore, replacing conventional aircraft with drones for aerial seeding is now being seriously investigated. With the rapid development of drone technologies over the past few years and improvements in direct seeding techniques, the time is right to explore the feasibility of aerial seeding by drone, to automate forest restoration. This paper, therefore, discusses to what extent lessons learnt from research on direct seeding can be applied to aerial seeding by drone and identifies future research needs to develop drones for aerial seeding.

FACTORS AFFECTING THE SUCCESS OF DIRECT SEEEDING

Direct seeding has been used in various types of conservation work, for example: i) to stabilize the vegetation and soil after fires (DODSON et al., 2009); ii) to rehabilitate mines; iii) to establish native plants on pastoral land or slash and burn agricultural land (BONILLA-MOHENO & HOLL, 2009) and iv) to enhance species richness in a late-successional target ecosystem (COLE et al., 2011). Successful seedling establishment and the speed and trajectory of subsequent succession depends on: i) site and species selection, ii) seed supply and quality, iii) site preparation, iv) sowing method and v) post-sowing management (DOUST et al., 2006).

Site and species selection

Selection of species for direct seeding often depends on matching species with the successional status of the site, but many studies are contradictory.

The species group most commonly selected for direct seeding on open degraded sites are the small-seeded, light demanding, pioneer species, because they are fast-growing and produce visible results rapidly (ENGEL & PARROTTA, 2001). Such species require full sunlight to trigger germination and for early seedling growth. However, selection of pioneer species for open areas does not always guarantee success (ENGEL & PARROTTA, 2001).

Where succession has already resulted in some shade, late-successional tree species with large seeds and shade tolerant seedlings usually perform better (SLIK, 2005). In Costa Rica, direct seeding of late-successional tree species was more successful under tree plantations than in pastures and secondary forests (COLE et al., 2011). In Hawaiian dry forest, seedlings of six tree species, established by direct seeding, survived better and attained higher biomass in beneath-canopy plots, than in more exposed plots (CABIN et al., 2002). Therefore, some late-successional species do well in more benign environments, although many do not express substantial differences, wherever they were sown (ENGEL & PARROTTA, 2001; DOUST et al., 2008).

DOUST et al. (2008) based species selection on the species composition of natural forest types near the restoration sites. She recommended mixing both fast-growing species (to capture the site and shade out the weeds) with slower-growing ones (to provide structural complexity) and monitoring interactions among the species to determine both the speed and trajectory of succession. In southern Thailand, germination and seedling establishment of both pioneer and late successional tree species (25 species tested) did not differ significantly in exposed deforested sites (TUNJAI, 2011). The poor establishment of either pioneer or climax species was likely caused by the weedy environment and/or the level of seed predation, although both of these factors can be minimized by site management. Successful species for direct seeding from around the tropics were reviewed in ELLIOTT et al. (2013).

Since tropical forests comprise so many tree species and many studies have failed to verify that species-site matching reliably predicts direct seeding success, experimentation with different species and subsequent monitoring are recommended for all direct seeding projects. With so many tree species to choose from, initial screening could help to narrow the field. Our previous research showed that, in general, tree species with seeds that are i) large or intermediate sized, ii) oval to round in shape and iii) with low to medium moisture content, tend to perform better in direct seeding experiments than most others (TUNJAI & ELLIOTT, 2012); these variables explained about 80% of the variability in the early success of direct seeding (see Chapter 6 for more on seed functional traits). If more detailed experimental data are available, then also look for: i) rapid and consistent germination (DOUST et al., 2008), ii) high rate of seedling establishment, iii) low sensitivity to competition (DOUST et al., 2008) and iv) adaptation to open environments with low/moderate-fertility soils.

Seed supply and quality

Drones have the potential to rapidly deliver very large numbers of seeds into deforested sites. Therefore, securing a large enough supply of seeds will be essential, if aerial seeding by drones is to become common practice. This will require detailed knowledge of the flowering and fruiting phenology of potential seed trees, to plan optimal seed collection schedules. The crown density method (KOELMEYER, 1959) is recommended for recording tree phenology because it is rapid and allows quantitative analysis of the data (ELLIOTT et al., 2013). A lack of availability of viable seeds from the target forest ecosystem, just prior to the sowing time can limit both the tree species and the numbers of seeds sown by drones, unless additional seeds could be obtained from other sources (e.g., community networks, seed banks etc.). Alternatively, seeds could be stored from collection time until optimal seeding time (usually the start of the rainy season). Unfortunately, the seeds of many tropical forest tree species are recalcitrant, i.e., sensitive to drying and chilling during storage. Such species must therefore be sown soon after seed collection, regardless of the prevailing climatic conditions at that time. On the other hand, seeds of orthodox species can be dried and chilled, so they can be accumulated over long periods in storage and sown in mixtures at the optimal time. Consequently, knowledge of seed storage behaviour is critical, when planning seed supply for large-scale direct seeding or aerial seeding projects. Seed quality is also critical. Seeds of desired species should be tested for viability and germination, to ensure appropriate seedling density when sown. After sowing, seeds with short dormancy tend to be less susceptible to desiccation and seed predation in deforested sites than those with longer dormancy (HAU, 1997; TUNJAI, 2005; WOODS & ELLIOTT, 2004). Useful information on breaking seed dormancy of tropical tree species can be found in the Tropical Native Species Reforestation Information Clearinghouse (TRIC) (http://reforestation.elti.org/).

Sustaining genetic diversity is also a critical consideration where restoration aims to conserve biodiversity. Seeds should be collected from as many different trees as is practical. Mixing seeds collected locally with those eco-geographically equivalent sources further afield is likely to capture more genetic diversity and give rise to new gene combinations, capable of adapting restored forests to environmental changes.

Site preparation

Weeding (mechanical or chemical) is essential prior to direct seeding. Glyphosate is the herbicide most commonly used for this purpose (DOUST et al., 2006). Herbicide usage reduces labour costs and avoids soil disturbance. Glyphosate is effective at killing weeds, but it probably also kills existing seedlings of native tree species. However, the susceptibility of native tree seedlings to glyphosate has not been assessed and genetic strains that are naturally resistant to herbicide may exist (see Chapters 9 & 10). Soils in abandoned agricultural sites are often compacted, which can constrain plant establishment and growth. The response of native forest tree seedlings to poor soil conditions varies greatly, due to differences in root structure. Mulching might ameliorate such harsh conditions and enable successful direct or aerial seeding of a wider range of less tolerant species. More research is needed to discover the functional traits (of both seeds and seedlings) that indicate tree species performance in the dry, hot, exposed conditions of deforested sites.

Fencing is recommended, to exclude grazers from eating or trampling young tree seedlings, but it cannot keep out insects, molluscs and small mammals, all of which may cause high mortality of direct seeded seedlings. Physical exclusion of smaller organisms is not practical when implementing direct seeding on large scales. Therefore, chemical repellents should be considered. Furthermore, fire breaks should be cut, particularly in seasonal dry tropical regions.

Sowing methods

The number of seeds per unit area (seeding rate), seed spreading method, timing and the density of existing vegetation must all be taken into account, when planning direct or aerial seeding. Optimal sowing density depends on both the site conditions and the species selected. The aim should be to space trees close enough to close canopy in 2-3 years whilst minimizing competition. To compensate for the low establishment rate of direct seeding (compared with tree planting), several seeds may be sown in each spot or seeding spots placed much closer together than would be done for tree planting (TUNJAI, 2011).

Hydroseeding involves seeds being "sprayed" in a slurry, containing processed woodchip fibres, fertiliser and a tackifying agent (DODSON ET AL., 2009). In forestry, it may be suitable for tiny seeds, such as those of fig trees, but the extra weight of the slurry probably precludes the technique from being adapted to drone-seeding. Mechanical seeding is commonplace in agriculture, spacing the seeds precisely to minimize competition. However, with forest trees, manual seeding produces the best results. For example, DOUST et al. (2006) showed that establishment rates were highest when seeds were manually buried, while broadcast-sowing resulted in very low seedling establishment. One offshoot from mechanical seeding has been the development of seed pelleting, initially to standardize seed size, to fit seeding machinery, but now being used to also deliver pesticides, nutrients and germination/growth enhancers to the germinating seeds (see Chapter 8). The technique has also been used with direct seeding of forest trees but with varying results. However, seed delivery devices, attached to drones, will most likely to require pelleting of seeds to a standard size, so further experimentation with pelleting of forest tree seeds is highly recommended.

Sowing time can significantly affect the outcome of direct seeding. In southern Thailand, direct seeding, early in the rainy season, resulted in higher germination and higher establishment rates, compared with late-sown seeds (TUNJAI, 2011). How-ever, in Australia, establishment rate of direct-sown seedlings was higher when seeds were sown later, due to reduced weed competition (DOUST et al., 2008). As explained above, however, sowing time is constrained by both fruiting period and seed storability. Recalcitrant seeds must be sown shortly after seed collection, whereas with storage, orthodox seeds can be sown at any time. Economics will decide whether it is more cost effective to accumulate orthodox seeds in storage and sow all species together, at the optimum time, or species by species, month by month, shortly after collection, together with recalcitrant seeds (WAIBOONYA, 2017).

Post-sowing management

Weeding and fertiliser application can counteract the low germination and seedling establishment rates, typical of direct seeding. Weed control can be especially important during early establishment, when seedlings are tiny (DOUST et al., 2008) and is usually achieved by spot herbicide application or manual weeding around seedlings (ENGEL & PARROTTA, 2001). Hand-weeding after direct seeding is recommended due to the difficulty of controlling herbicide spray, although application of the grass-specific herbicide, Fusilade, two months after direct seeding, has proved effective (DOUST et al., 2008). However, some studies question the effectiveness of weeding. In Thailand, weed removal had no significant effect on germination (in the first year after sowing) and highly variable, species-specific effects on seedling survival (TUNJAI, 2005). In the dry season, weeds might actually protect small seedlings from desiccation, although they are also a fire risk.

Whereas fertiliser application almost always improves the survival and growth rates of planted trees, its effects on direct-seeded seedlings are variable. Counterintuitively in southern Thailand, fertiliser application actually decreased early establishment of forest tree seedlings in the first year after direct seeding (TUNJAI, 2011), whereas it had no effect in Brazil and Central Amazonia on extremely poor soils (ZANINI & GANADE, 2005). Different tree species require different amounts of nutrients in different habitats and the doses of fertiliser applied in the above experiments may have been too low to exceed loses due to leaching, denitrification and immobilization. If fertiliser really does have no effect in the first year after sowing, then this would obviously reduce the costs of direct or aerial seeding.

FURTHER RESEARCH

The above review highlights the variability in the response of different tree species in different habitats to the treatments that can be applied to improve direct seeding success. Clearly further research is needed to determine the most appropriate species-specific and habitat specific treatments. When making the leap from direct seeding to aerial seeding by drone, 3 additional factors come into play: i) enabling seeds to survive the drop, ii) seed burial and iii) automated maintenance.

Seeds dropped or propelled from drones will almost certainly have to be protected within some kind of projectile or pellet (seed “bomb”). Further research should concentrate on seed bomb design (materials, shape) and the composition of the germination medium contained (hydrogels, fertilisers, pesticides, germination enhancers etc.), particularly with regard to cushioning seeds from impact with the ground. The seed delivery system should ensure that seeds are buried as much as they would be, if sown by hand, since seed burial is one of the few treatments which appears to be generally effective (DOUST et al., 2008). Seed size is probably the most important characteristic that will influence seed bomb design, which will in turn will affect the design of delivery mechanisms, along with optimum sowing density, substrate hardness and whether gravity or propulsion is used to deliver seeds into the soil. Aerial seeding of large, inaccessible areas makes no sense if on-the-ground human intervention is subsequently required for weed control. However, automated weed control around the tiny seedlings that emerge from aerial seeding is highly problematic (Chapter 9 & 10). Matching herbicides sprayed from the air with the most competitive weed species, smart spraying or developing other techniques such as laser cutting, liquid mulching or selection of weed resistant or herbicide resistant tree species will become essential if drone-seeding of large, inaccessible areas is to become a viable proposition.

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Figure 5.4 - A new forest arises, 3 years after direct seeding (Krabi, S. Thailand). But are lessons learned from such experiences transferrable to drone-seeding?

(Photo - K. Naruangsri)

Figure. 6.1 - Variation of seed size of five tree species native to Northern Thailand. From left to right: *Hovenia dulcis* Thunb., *Prunus cerasoides* Buch.-Ham. ex D.Don, *Alangium kurzii* Craib, *Choerospondias axillaris* (Roxb.) B.L.Burtt & A.W.Hill and *Horsfieldia amygdalina* (Wall.) Warb.

(Photo - K. Naruangsri)

Figure. 6.2 - Seeds collected from mother trees to be sown in a tree

Chapter 6

A TRAIT-BASED APPROACH FOR SELECTING TREE SPECIES FOR AERIAL SEEDING

Noelle G. Beckman[1] and Pimonrat Tiansawat[2]

ABSTRACT

We review recent ecological research on functional traits that can aid selection of tree species for restoration by aerial seeding. A major barrier in selecting species for restoration of hyperdiverse tropical forests is a lack of silvicultural and ecological information. Functional traits give insight into the potential performance of tree species in deforested sites and provide a mechanism to scale up from individual tree performance to ecosystem functions. Using relatively easy-to-measure functional traits may be an effective way to screen the suitability of tree species for aerial seeding for automated forest restoration. Aerial seeding would be particularly useful to restore forest in remote or isolated sites, where extirpation of vertebrate seed dispersers limits natural seed dispersal. Therefore, we focus on selecting tree species, based on fruit traits, to enhance restoration via aerial seeding.

Key words**:** functional traits, seed bombs, restoration, aerial seeding, stage of degradation, seed germination

A TRAIT-BASED APPROACH FOR RESTORATION

Throughout their life cycle, plants undergo a multitude of interactions with other organisms, from mutualisms with seed dispersers and nutrient-foraging microorganisms, to antagonistic interactions with competitors, pathogens and seed predators (Fig. 6.4). In response to these interactions and the abiotic environment, plants have evolved a diversity of strategies to grow, survive and reproduce during their sedentary lives. These life history strategies are influenced by functional traits that mediate plant growth, survival, and reproduction (REICH et al., 2014). Such traits include the morphological, physiological and phenological traits (VIOLLE et al., 2007)

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that influence the ability of plants to acquire and conserve resources, disperse into new habitats, and defend themselves against herbivores and pathogens. Studies of variation in functional traits have revealed fundamental tradeoffs (e.g., WESTOBY et al., 2002; DIAZ et al., 2016) that relate to trade-offs in growth, survival, and reproduction (ADLER et al., 2014).

The burgeoning body of global databases and ecological studies on variation in functional traits and their relationships with plant performance and demography now enable the responses of unstudied plant species to be predicted in variable environments (e.g., KATTGE et al., 2011; SALGUERO-GÓMEZ et al., 2015). This is important in hyperdiverse tropical forests, where it is logistically impractical to conduct all the necessary ecological and silvicultural studies needed to develop conservation plans and management strategies. For most species, data on plant performance in different environments are lacking. Using easily measurable traits, which give insight into the germination, growth and survival requirements of species, may be an effective way to select plant species for restoration (OSTERTAG et al., 2015) and help foresters to select appropriate tree species for aerial seeding, to restore areas with different degradation stages. A functional trait-based approach can be used to incorporate aerial seeding into existing forest restoration strategies, including both the framework species and maximum diversity methods (ELLIOTT et al., 2013).

In 1994, Chiang Mai University's Forest Restoration Research Unit (FORRU-CMU) began adapting the framework species method to restore seasonally dry, upland, evergreen forest to degraded sites in northern Thailand. Originally conceived in Queensland, Australia (GOOSEM et al., 1995), the method involves selecting native tree species that are characteristic of the target forest type and enhance natural forest regeneration. Seedlings, 30-50 cm tall, of 20-30 framework tree species are planted out in degraded sites and nurtured for two rainy seasons by weeding and fertilizer application. FORRU-CMU has carried out both nursery and field research to determine which species meet the criteria of framework tree species for forest restoration. Such selection criteria include ease of propagation in the nursery, high seedling survival and growth after transplantation into exposed deforested sites, dense spreading crowns to shade out weeds, and attractiveness to seed-dispersing animals (through the early provision of fleshy fruits, nectar, nesting sites etc.) (BLAKESLEY et al., 2000). The latter is particularly important in the tropics, where most tree species depend on vertebrates for seed dispersal (BECKMAN & Rogers, 2013).

A limitation of the framework species method is that it requires nearby remnant forest to provide a diversity of seed sources and habitat for seed-dispersing animals for natural regeneration. Globally, vertebrates are declining rapidly due to hunting, habitat destruction, climate-change and invasive species (DIRZO et al., 2014). Larger-bodied vertebrates are more susceptible to extirpation, due to hunting and habitat loss, than are smaller-bodied animals. Furthermore, large-seeded species rely on these large-bodied vertebrates for dispersal (STONER et al., 2007; BRODIE et al., 2012 & MARKL et al., 2012). Decline in vertebrate abundance creates another major challenge for restoration approaches that rely on vertebrate seed-dispersal – a challenged being address by “maximum diversity methods” of restoration. These involve planting saplings of all (or as many as possible) species that meet restoration objectives (ELLIOTT et al., 2013), together with intensive site preparation, to ensure their survival. Plantings can be done in one or several stages, sometimes by planting pioneers first, followed by late-successional species afterwards (ELLIOTT et al., 2013).

Where vertebrates have been extirpated, seeding by unmanned aerial vehicles (UAVs), planes, or helicopters could be implemented. While seedling performance, in the nursery and in the field, are primary criteria when selecting species for both methods, other characteristics must also be considered when substituting tree planting with aerial seeding. Plant mortality, due to abiotic environmental filters, predation (Fig. 6.4) and diseases, is highest during the seed-to-seedling transition. Therefore, selection criteria for aerial seeding should include a set of seed traits that promote seed germination, desiccation tolerance, predator deterrence, pathogen resistance, and the ability to outcompete weeds.

The optimal strategy for restoring forest ecosystems, depends how degraded the restoration site is. ELLIOTT et al., (2013) provided a concise classification of degradation stages, based on critical shifts in regeneration potential that require fundamental changes in restoration approaches. They classified five stages of degradation, based on remaining vegetation, seed sources for natural regeneration, soil conditions, nearby natural forest remnants, animal dispersal agents and fire risk (ELLIOTT et al., 2013). Stage 1 is the least degraded, with trees dominant over herbaceous weeds, and soils mostly fertile. Protecting Stage-1-degradation sites from cattle, fire and other disturbances is usually sufficient to facilitate natural regeneration. A mix of trees and weeds, rarity of large seed-dispersing animals, and medium to high fire risk characterize Stage-2 degradation. In Stage-3, weeds are dominant, fire risk is high, and small seed-dispersing animals remain present. In Stages 4 & 5, seed-dispersing animals have mostly been extirpated, forest remnants are too distant or too sparse to serve as seed sources and soils are at higher risk of erosion. Additionally, poor soil conditions in Stage-5 can limit the growth of herbaceous weeds and establishment of trees.

SPECIES SELECTION FOR AERIAL SEEDING, BASED ON FUNCTIONAL TRAITS

In selecting species for aerial seeding, practitioners should consider which values of seeds traits are most suitable for each degradation stage. In Table 1, we highlight seed traits to consider when selecting native species for aerial seeding to restore sites at various degradation stages, including seed size (Fig. 6.1), seed defense, seed germination and desiccation tolerance.

Table 1. Recommendations for Aerial Seeding. Degradation stages described in Elliott et al. (2013) and summarized in the text

Degradation Stage	Vegetation	Traits
Stage 1	Trees dominate	Aerial seeding not necessary, unless forest remnants are too far to provide seed sources or vertebrates locally extirpated
Stage 2	Mixed trees and herbaceous weeds	Large seeds preferable Seeds with high investment in seed defence
Stage 3	Herbaceous weeds dominate	Mixture of large and small seeded species Desiccation tolerance Rapid germination
Stage 4	Herbaceous weeds dominate	High proportion of species with small seeds Desiccation tolerance Rapid germination
Stage 5	No tree cover and few weeds	Aerial seeding not recommended without intensive site preparation e.g., provision of shade soil/substrate amelioration

Desiccation tolerance of seeds in storage

The ability to store seeds should be considered when selecting species for aerial seeding. Storing seeds after seed collection (Fig. 6.2) is necessary when (1) seeds are collected when immediate aerial seeding is not suitable, (2) seeds must be transported to areas where seeds are unavailable and (3) seeds are not available every year (FOREST RESTORATION RESEARCH UNIT, 2005). Desiccation tolerance determines whether seeds can be stored dry. Species can be categorized into three groups, according to their degree of desiccation tolerance. Orthodox seeds tolerate dry conditions without physiological damage. Intermediate seeds tolerate being dried to approximately eight percent of initial moisture, but cannot withstand low storage-temperatures. Recalcitrant seeds are sensitive to desiccation and therefore cannot be stored dry. About 10 – 45% of tropical tree species have recalcitrant seeds, depending on habitat and location (TWEDDLE et al., 2003), so sensitivity to desiccation limits seed storage of a very large number of tree species and consequently limits their potential use for aerial seeding. Storage tolerance, or the lack of it, plays a major role in determining which species can be used for aerial seeding and at what times of the year aerial seeding can be carried out.

Several seed traits are correlated with desiccation tolerance during seed storage. However, the correlations between traits and desiccation tolerance are complex and one trait alone is not a good indicator. Several studies have shown that desiccation tolerance depends on seed size, covering structures (endocarp and testa), dormancy, and species' successional status (see TWEDDLE et al., 2003; PRITCHARD et al., 2004; DAWS et al., 2005; LAN et al., 2014). Desiccation tolerance decreases with seed size, as larger seeds (>3000 mg) lose viability quickly after being dried compared with smaller seeds (PRITCHARD et al., 2004; DAWS et al., 2005; DAWS et al., 2006). However, within desiccation tolerant and desiccation sensitive species, seed size varies across five orders of magnitude (PRITCHARD et al., 2004). Therefore, seed size alone is not a useful indicator of likely desiccation tolerance. The second correlative trait is investment in seed covering structures. Desiccation tolerance increases with thickness of covering structures (DAW et al., 2006). The mass ratio of seed covering structures to total seed mass (SCR) is used in predictive models of desiccation tolerance. These models show that species with low SCR are more likely to be sensitive to desiccation (DAWS et al., 2006; LAN et al., 2014). Low SCR indicates a thin seed covering structure in relation to total seed size. Large seeds with "thin" seed covering structures are therefore less likely to survive drying.

Seed dormancy also appears to be linked with desiccation tolerance. Non-dormant seeds are those able to germinate when seeds are placed under suitable conditions (BASKIN et al., 2004), whereas dormant seeds are those that do not germinate, even when conditions appear suitable for germination. Seed dormancy may be caused by physical, physiological, morphological or morphophysiological factors (BASKIN et al., 2004). Desiccation-sensitive seeds (recalcitrant) can be found more frequently among non-dormant than dormant species. However, not all dormant seeds are orthodox because of different types of seed dormancy. It is likely that species with water-impermeable seed or fruit coats (physical dormancy) have orthodox seeds. However, exceptions exist for species with other dormancy types (TWEDDLE et al., 2003).

The successional status of species is another factor that relates to desiccation tolerance. Species can be classified as either pioneer or late successional species. Pioneer species require full sunlight for seed germination (Fig. 6.3) and rapid seedling growth. They can therefore colonize open areas, after disturbance (SWAINE et al., 1988). In contrast, late successional species establish after canopy closure and can tolerate shade. Seeds of late successional species are commonly desiccation-sensitive, whilst those pioneer species are split equally between recalcitrant and orthodox species (TWEDDLE et al., 2003).

For aerial seeding, it is easier to handle seeds of desiccation-tolerant species (orthodox seeds) than desiccation-sensitive species (intermediate or recalcitrant seeds). However, practitioners should not omit entirely those species with desiccation-sensitive seeds from aerial seeding, because some of them may provide important ecological functions (e.g., food sources for animals, shade to impede weeds, etc.). Therefore, the seed storage behaviour of species should be determined before planning seed-handling techniques and aerial seeding. As described above, desiccation tolerance can be inferred from a combination of traits, including seed size, mass ratio of seed covering structures to total seed (SCR), seed dormancy, and successional status. With aerial seeding, it is possible to overcome seed-storage limitations by using seed containers and/or seed pelleting (see Chapter 8).

Germination response to desiccation

While information on the desiccation tolerance of seeds can guide the selection of species that can be stored before aerial seeding, information on the germination response of different species to desiccation can aid the selection of species that have an increased chance of survival and establishment in degraded areas. Seed germination depends on site conditions, such as light availability, gas exchange and soil-moisture availability (Fig. 6.3). In particular, soil dryness can limit seed germination, because imbibition of water is an essential germination trigger. In large, open, degraded sites (e.g., Stage-3-degradation or higher), surface soil can dry to the permanent wilting point after only six days without rain (ENGELBRECHT et al., 2006). Therefore, species selection for aerial seeding should consider trait values that indicate high survival and germination at particular degradation stages. In addition, germination success can be modified with seed enablement technologies (see Chapter 8).

Information on seed traits can help guide the selection of species that can tolerate dry conditions. In dry areas, selecting a species mixture that includes a large proportion of drought-tolerant species could increase the chances of success. For example, in seasonally dry tropical forests, larger tree seeds tend to germinate better than smaller ones do under drier conditions (KHURANA et al., 2004; DAWS et al., 2008). However, the relationship between seed size and germination response to desiccation is not universal. In the aseasonal humid tropics, seed size is not correlated with the ability to germinate under dry conditions. Smaller seeds can also germinate under dry conditions and can germinate faster than larger seeds do (TIANSAWAT, 2013). The ability of smaller-seeded species to germinate under dry conditions is determined by their successional status (TIANSAWAT, 2013). Small seeded pioneer species that can regenerate in desiccation-prone environments can germinate under drier conditions than shade-tolerant species can (i.e., late successional species) (TIANSAWAT, 2013). Seed size and plant successional status can indicate germination success under unpredictable, dry site conditions. We suggest selecting a mixture of large and small seeded where drought is likely, such as Stages-3-4 degradation, and selecting a higher proportion of smaller-seeded pioneer species for Stage 4 (Table 1).

Predation and Herbivory

Seed predation (Fig. 6.4) and seedling herbivory (Fig. 6.5) can be high in the tropics (COLEY et al., 1996; HULME 1998). Seed predation and herbivory vary with degradation stage. Less degraded areas tend to have more animals (BLACKHAM et al., 2015), with potentially higher risk of seed predation and herbivory in Stages-1-2 degradation compared to Stages-3-4. Less degraded areas are more prone to higher seed predation and herbivory (BLACKHAM et al., 2015), so species should be selected with trait values that deter or tolerate seed predation and herbivory. Functional traits are correlated with seed predation by vertebrates and insects and susceptibility to disease. Smaller seeds may escape predation by being more easily buried (LEISHMAN et al., 2000). LEISHMAN et al., (1994) predicted that larger seeds are more attractive to seed predators, because they have larger energy reserves, but they are also more tolerant to predator attacks (DALLING et al., 1997). Larger seeds also take longer to germinate because of a long imbibition time until radicle emergence, compared to smaller seeds. Remaining in the seed stage on the soil surface for longer allows more time for seed predation and pathogen infection to occur. Larger seeds produce larger seedlings, which may be more tolerant of herbivory (ARMSTRONG et al., 1993). In species whose seeds contain multiple embryos (e.g., *Antirhea tricantha*, *Choreospondias axillaris*), the number of locules (embryos) within a propagule also increases the probability of escaping insect seed predation (BECKMAN et al., 2011). In addition to size, seed defense mechanisms can help protect seeds from predation. Seeds with more physical and chemical defenses may be less susceptible to predation (MOHAMMED-YASSEEN et al., 1994) and pathogen attack (WHITEHEAD et al., 2014). For example, thicker seed coats may protect seeds from pathogens (BECKMAN et al., 2011) and insects (THEIRY 1984; KITCH et al. 1991). However, there may be tradeoffs between physical and chemical defenses (TEWKSBURY et al., 2008). Where seed predators and herbivores are abundant, we suggest selecting species that have higher physical or chemical defenses, to deter seed predators and pathogens (Table 1).

Abiotic Environmental Filters

Functional traits, related to the acquisition and conservation of resources, can indicate whether a plant can survive and grow under prevailing environ-mental conditions. Several studies show that plant species with traits that enable resource conservation when resources are limiting, tend to have low growth rates and high survival rates, compared with species with traits for rapid resource acquisition when resources are more abundant (REICH et al., 2014). For example, plants with higher wood density tend to have higher survival (KRAFT et al., 2010; WRIGHT et al., 2010) and, in some cases, slower growth rates (CHAVE et al., 2009). Wood requires a lot of carbon for its synthesis, but it provides trees with biomechanical support needed to grow above competing plants. Higher wood density (dry mass divided by green volume) correlates with a tree's ability to resist mechanical breakage, drought-induced embolism, and pathogens (CHAVE et al., 2009; KRAFT et al., 2010). Investing carbon and energy in higher wood density is therefore a conservative strategy that enables plants to conserve limited resources through increased protection and survival.

Several studies have shown that seedlings from larger seeds have higher establishment rates (TUNJAI et al., 2012; VISSER et al., 2016), lower seedling growth rates, and survival rates that depend on seedling size (VISSER et al., 2016). Larger seeds produce larger seedlings, making them better able to tolerate hazards. As larger seedlings have deeper roots, they are less susceptible to dry conditions and disturbance by animals (Coomes et al., 2003). Khurana et al. (2004) showed that, under water-stress, seedlings from larger-seeded tree species suffer lower mortality compared with those of smaller-seeded tree species. Seed size is loosely related to shade-tolerance (Coomes et al., 2003), although a few small-seeded species can persist under shade (Grubb, 1998).

Competition

Competition among young plants for limited resources is a key ecological process in forest restoration and strongly influences successional dynamics. As environmental conditions change with degradation stage and succession, so does the competitive hierarchy within the plant community. Under moderate degradation stages (Stages 3-4), tree species selected for aerial seeding must be able to outcompete weeds at the seed and seedling stage.

Time of germination and seed morphology are important in determining the success of competition. Small-seeded species may germinate rapidly but their resultant small seedlings may not be able to compete well for resources, particularly where water and light are severely limited. Larger seeds tend to be better competitors (Turnbull et al., 1999; Coomes et al., 2003). Diaz et al. (2016) showed that species with larger seeds tend to have taller maximum adult heights, a measure of plant size that indicates the competitive ability of plants to preempt light resources as taller plants display leaves over smaller plants.

At higher degradation levels (Stage 4), we suggest selecting small-seeded, light-demanding species that have high seedling growth rates, to capture light and space before herbaceous weeds become dominant and subsequently planting larger-seeded species that have slower growth rates, but larger maximum heights that can outcompete weeds long-term.

Trade-offs among traits

Trade-offs in functional traits occur when one trait value increases whilst another one decreases. They can be inferred from a negative correlation between two traits. For example, species may trade the ability to compete for one limited resource for the ability to compete for another limited resource (Grime 2002; Fortunel et al., 2012) or trade the ability to colonize new areas with the ability to compete for a limited resource (Tilman, 1994; Levine et al., 2002) or tolerate environmental stresses (Muller-Landau, 2010). Trade-offs in functional trait values relate to trade-offs in plant performance (Adler et al., 2014). These trade-offs among traits and plant performance constitute a challenge when selecting species that meet all species criteria for aerial seeding and restoration. For example, there is a trade-off between seed size and the numbers of seeds produced (MULLER-LANDAU, 2008; VISSER et al., 2016). Species with large seeds (e.g., *Afzelia xylocarpa*) produce fewer seeds compared with small-seeded species (e.g., *Ficus* spp.). Therefore, it may be easier to obtain smaller seeds. However, small seeds tend to be less competitive (TURNBULL et al., 1999; COOMES et al., 2003) and have lower tolerance to environmental stresses (COOMES et al., 2003). Hence, collecting a sufficient number of seeds of species with trait values that reflect optimal survival, establishment, and competitive ability for the purpose of restoring degraded areas may be challenging. Selecting a range of species that have a mixture of functional trait values may be the best approach.

RECOMMENDATIONS

Selecting species for aerial seeding depends on the degradation stage, as discussed above. Combining knowledge of framework tree species and maximum diversity methods with trait data is useful for preliminary screening of potential species that are suitable for aerial seeding. This relies on availability of trait data for species in the study system from floras, target forest surveys, indigenous local knowledge, and research conducted on species within the area of interest (ELLIOTT et al., 2013). If species-level information is not available, information from closely related species can be used, because they tend to be more functionally similar than distantly related species (SWENSON et al., 2007). Surveying relevant traits that are quick and inexpensive to measure could be integrated into forest surveys, if little information is available from previous research, floras, or indigenous local knowledge. A trait-based approach can help prioritize whether an unstudied species may meet the criteria for restoration by aerial seeding and merit further investigation with experiments.

We suggest that aerial seeding could be used to replace or complement tree planting for sites at degradation Stages-2-4. Depending on the availability of seed sources and abundance of vertebrate seed-dispersers, aerial seeding could be useful for remote sites, where conventional tree planting is more difficult. Restoring forest to sites at Stages-1-2 degradation relies on manipulating natural regeneration, to bring about canopy closure (no tree planting necessary). Consequently, aerial seeding would only be necessary if seed sources (forest remnants or scattered remnant trees) are too distant to provide seed inputs into the restoration sites or if vertebrate seed dispersers have been locally extirpated. For the most severely degraded sites (Stage-5), aerial seeding would not be effective, unless soil remediation measures are also implemented.

Seeds, representing the full functional diversity needed to attain restoration objectives, could be dropped all at once or with different species added in stages. Many tropical seeds are recalcitrant and germinate at the beginning of the wet season, so a challenge will be time of seed collection and dropping seeds before they desiccate. If dropping mixtures of species, all at once, proves to be impractical, different species may be dropped at different times of the year (depending on fruiting times). We recommend dropping large seeds in either the first stage or second stage of restoration, across all degradation stages, as large-seeded tree species are more likely to have lost their seed dispersers (STONER et al., 2007; BRODIE et al., 2012; MARKL et al., 2012). Species that are heavily defended with thick seed coats or chemicals are good choices for restoration, where vertebrate seed predators are present.

OTHER CONSIDERATIONS

Though not discussed here, the spatial arrangement of seeds and seed bombs (Chapter 8) should also be considered, as this can affect interspecific competition (BOLKER et al., 2003), as well as seed predation and infection by pathogens (BECKMAN et al., 2012). Models can be used to simulate different restoration strategies to explore the influence of the spatial arrangement of seeds and seed bombs on growth and survival of selected species and help choose a spatial distribution of seeds with a diverse set of functional traits to achieve restoration objectives.

Finally, a trait-based approach can be used to select species that meet overall ecological and social restoration objectives and achieve a self-sustaining system (ELLIOTT et al., 2013) and reduce future interventions. Integrating empirical information on functional traits with quantitative ecological models, practitioners can explore the expected community and ecosystem dynamics under different restoration scenarios and whether model predictions meet restoration objectives (LAUGHLIN, 2014). Theoretical underpinnings of restor-ation are discussed in more detail by LAUGHLIN (2014), and a practical example is provided by OSTERTAG et al. (2015).

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(Photo - K. Naruangsri)

Figure. 6.3 - Germination of *Alangium kurzii* after seed sowing in a direct seeding experimental plot in Chiang Mai, Thailand

(Photo - K. Naruangsri)

Figure. 6.4 - Seed covering structures of *Prunus cerasoides* left behind by seed predators.

(Photo - K. Naruangsri)

Figure 6.5 - Herbivory of a young seedling

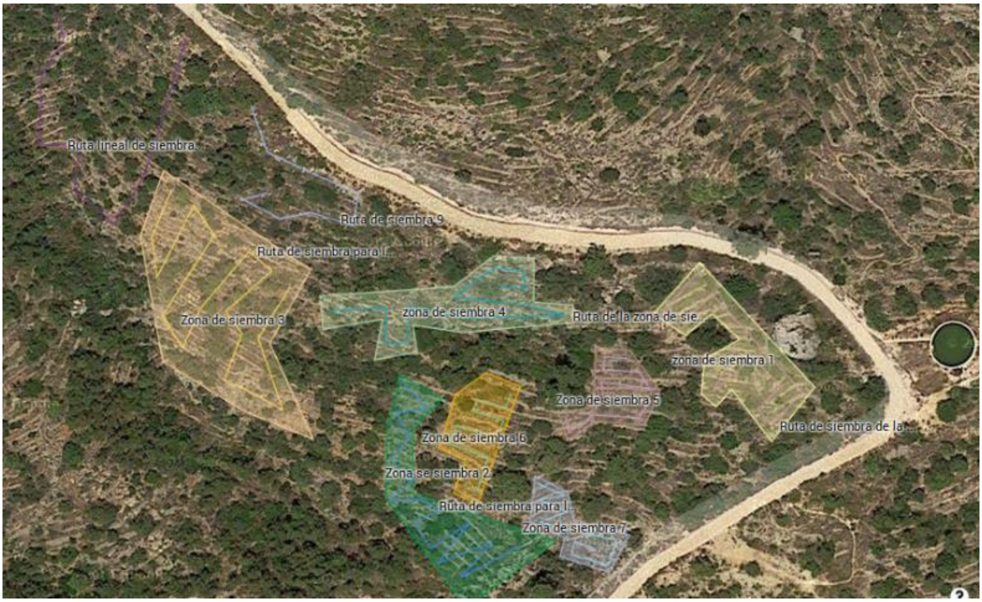

Figure 7.1 - Aerial image and seed dispersal plan of Montgo Natural Park, western flank, September 2015

Figure 7.2 - 3D-Robotics' Y6 hexacopter adapted to carry two seed dispensers

Chapter 7

Aerial Robotics for Forest Management and Seeding

Lot Amorós[1] and Jesus Ledesma[2]

ABSTRACT

Dronecoria is a reforestation project that uses customized DIY drones to disperse seeds ("dronechory") in clay balls. Unlike traditional aerial seeding techniques, which often depend on exorbitantly expensive air craft and support facilities and personnel, dronecoria relies on low-cost mechanisms, borrowed from cybernetics, robotics, permaculture and digital manufacturing, to sow seeds from inexpensive drones, with wooden recyclable frames. Using drones to scatter seeds allows accurate positioning of seeds, to potentially maximize seed germination and seedling survival.

Key words: Drones, UAV, quadcopter, mapping, aerial seeding, nendo dango, permaculture, Masanobu Fukuoka

SOCIO-ECOLOGICAL BACKGROUND

Rising to 753 m above sea level, Montgó mountain is home to some of the most unusual flora and fauna in Spain. Part of the Cordillera Prebética Range in Alicante Province, the mountain is a national park, renowned for its rock formations, cliffs, caves and natural harbours. In May 2014, 39.5 ha of the western flank of the mountain, near Barranc de l'Hedra, caught fire and the vegetation was destroyed. Several organizations were mobilized to restore vegetation to the burnt areas. Foundation "Embracing the World", was created in La Marina Alta (Alicante) and took charge of the restoration work. Initial goals were to:

1. assess the state of the ground after the fire,
2. prepare the area for restoration,
3. create tools to assist in the ecological restoration and
4. plant native forest tree species.

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SITE DESCRIPTION

The project was implemented on 1 ha of the 2,057 ha of Denia municipality, "Monte de Utilidad Publica Montgó II", cadastral parcel No. 177, Denia polygon 11 on predominately Cretaceous substrates, with some Triassic and Quaternary substrates also present, on loamy limestone. Annual temperatures average about 17˚C and annual rainfall averages about 700 mm, with most occurring during the fall, although in recent years, rainfall has decreased, resulting in droughts.

Mediterranean ecosystems are fire-prone, but this site is particularly so, due to a high density of Aleppo pines (*Pinus halepensis*) planted in the 1950s at higher densities than would occur naturally. However, in less than two years after the 2014 fire, perennial plants (e.g., carob, olives, mastic, Kermes oak, heather etc.) have resprouted. Dominant plant species include dwarf fan palm (*Chamaerops humilis*), mastic tree (*Pistacia lentiscus*), garden thyme (*Thymus vulgaris*), Aleppo Pine, carob (*Cerotonia siliqu*a) and various herbs e.g., *Psoralea bituminosa, Brachipodium retusum,* among others. We also found almond trees, together with *B. retusum* in beds of crushed litter, pioneer asparagus in stony areas and wild thyme, growing in an area covered with *Hyparrhenia* grasses.

UNMANNED AERIAL VEHICLES TO RESTORE A MEDITERRANEAN ECOSYSTEM

Due to the ecosystem properties and the possibilities provided by new technologies, we adopted a strategy of precise aerial seeding by drone of the 3 vegetation layers: i) the herbaceous layer (i.e., grasses and legumes, colonizers and ground cover), ii) shrubs of various sizes and in lower proportion iii) some trees, mainly of edible species.

Strategic seed-sowing is now possible by aerial robotics, because of the precision and control provided by GNSS (Global Navigation Satellite Systems) (Fig. 7.2).

Restoration protocol:

1. Carry out a pre-restoration site assessment: topography, flora and fauna, and water flow (Fig. 7.1).
2. Collect seeds, culture microorganisms, and produce seed pellets (nendo dango).

3. Develop a seeding plan (following a permaculture design) to determine the best combination of seed species for each part of the restoration site.
4. Plan shortest flights needed to deliver each seed species to its appropriate points.
5. Perform the seed dispersal flights.
6. Monitor seed germination and seedling growth across the site.

The Flone quadcopter as a tool for data collection

We used the open-source quadcopter, Flone[3] (Fig. 7.3 & 7.6), to map the site, using a servo gimbal for nadir camera stabilization. Images were taken in the visible spectrum (Fig. 7.1), using a relatively inexpensive camera (Infragram Point-and-Shoot[4] from PublicLab[5]). Image resolution was largely determined by the elevation of the camera. Flights at 80-m altitude achieved resolutions of 3 to 5 cm/pixels. From these images, NDVI (Normalized Difference Vegetation Index) maps were constructed. The system was low cost, with the quadcopter costing approximately US$120 and the camera costing US$125. Since the system was self-built (DIY), it could be easily repaired on-site.

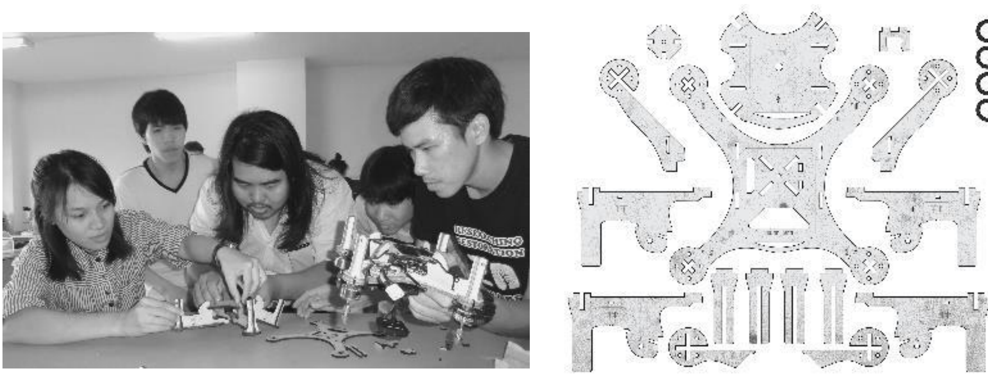

Figure 7.3 – The Flone frame comes as components, cut by laser into a sheet of plywood. Each part is pressed out from the sheet and assembled like a three-dimensional jigsaw. The frame is therefore cheap, easy to repair and biodegradable.

[3] Flone, open-source quadcopter, available at: http://flone.cc (Fig. 7.6)

[4] Camera documentation available here: https://publiclab.org/wiki/infragram-point-shoot

[5] The Public Laboratory for Open Technology and Science (Public Lab) is a community, which develops and applies open-source tools, for environmental exploration and investigation.

Planting plan development

Initially, we took photographs in the near-infrared, to increase visibility of plants, since they reflect mainly in the infrared spectrum. However, since the effects of erosion and burning were noticeably clear, in the end, near-infrared photos were not necessary. We analyzed the pictures and decided to seed the most vulnerable areas, i.e., those eroded by surface runoff and without vegetation cover.

Nendo dango

Aerial seeding by drone requires less effort than the conventional method of raising tree saplings in nurseries, transporting them to the site, hole digging and post-planting maintenance (weeding and fertilizer application). Even though the percentage establishment of aerially seeded plants is low (due to predation and desiccation), we found that the roots of those that *do* establish rapidly penetrate deep into the soil.

Our use of seed pellets was inspired by the agricultural practices of permaculture (ALLEN, 2006) and by those devised by Masanobu Fukuoka (FUKUOKA, 2013). Nendo Dango means "soul of the earth in your hands", representing the potential of life, concentrated in the clay pellets (Fig. 7.4).

Each of our pellets contained a few seeds, mixed with a cocktail of native micro-organisms and plant-based seed-predator repellents (e.g., pepper, chili powder, tobacco or thyme).

The ideal composition of the aerial Nendo Dango was:

- dry native microorganisms solidified,
- 1/4 of basaltic stone powder,
- 1/4 of seed mix (2% of the soil quantity approximately),
- a handful of predator repellents: black pepper, tobacco, chili and thyme,
- liquid binder (water or liquid microorganisms),
- clay powder to completely cover the seeds.

Clay proportion, strength and porosity

Tests were performed to ensure that the clay balls did not break up when dropped from a UAV. Experiments with mixing poultry manure and microorganisms with either rice husk or wheat bran, increase the porosity and elasticity of the clay balls were inconclusive; further tests are needed.

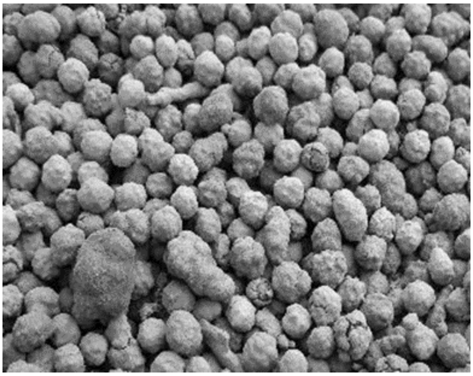

Figure 7.4 – "Nendo Dango"

Figure 7.5 - Surface microbiological culture

Basaltic rock powder

Being an igneous, volcanic rock, basalt has not been weathered or otherwise transformed by environmental processes. Therefore, the rock retains its full complement of minerals and plant nutrients, with no leaching of trace elements or micronutrients. This contrasts with the depleted substrate of the burnt and leached restoration site. Therefore, addition of basaltic rock powder to the Nendo Dangos might improve provision of plant nutrients to the germinating seedlings, although this needs additional testing and verification.

Microbiology

Forest soil supports a great diversity of the micro-organisms that are fundamental to soil ecology and plant development. The purpose of incorporating microbes into the Nendo Dango (Fig. 7.5) is to protect seeds from pathogens, increase their germination, to boost restoration, by breaking down organic matter and increasing plant nutrient availability. The microbial cocktail, prepared by J. Ledesma consists mainly of bacteria (*Lactobacillus* species, and fungi spores), particularly those species capable of decomposing pine-needle litter.

Seed species selection

After assessment of site conditions, we propose selecting a mix of seed species for habitat restoration that enhance soil fertility and ameliorate soil physical conditions, thus promoting establishment of woody plants and recolonization by wildlife (e.g., rabbits and partridges).

The green manure seed mix, use at Montgó, consisted of *Avena* spp and *Vicia* spp, applied in a ratio of 2:1. The former are oats (grasses), whilst the latter are vetches (legumes); nitrogen-fixing herbs. Although indigenous, wild, green-cover species, such as *Psoralea bituminosa* and *Brachipodium retosum* (a ground covering grass), were preferred, their seeds were not available. Other recommended seed species included Buckthorn (*Rhamnus alaternus*), kermes oak (*Quercus coccifera*), lavender (*Lavandula dentata*), Phoenician juniper (*Juniperus phoenicea*), dwarf fan palm (*Chamaerops humilis*), madrone (*Arbutus unedo*), heather (*Erica sp.*) and wild thyme (*Thymus mastichina*).

Mass production

The mechanical process of making the seed pellets was derived from Fukuoka (2013), using a "nendodanguera". We adapted a concrete mixer without the blades. The seeds were placed in the mixer and moisture was gradually added by spraying, along with the clay powder and the rest of the materials. Within a few seconds, the clay was deposited around the seeds, resulting in nendo dangos, which were then left to dry in the sun for storage and prevent germination.

Flight planning

Flight paths were designed with the open-source software DroidPlanner, available for Android devices. Once the areas to cover were defined by drawing spots, lines, or areas, the resulting flight paths were uploaded to the drone and executed.

Seed-dispersal flights

3D-printed seed-release system

Together with Salva Serrano[6], we designed a 3D-printed seed-release system (Fig. 7.7) attached to a re-used PVC drinking bottle, analogous to a screw tap. Bottles were used for storing nendo dango pellets and for aerial dispersal by drone. The release mechanism was in the neck of the bottle, with an automatic aperture controlling the flow rate of the seeds.

[6] https://salva-serrano.com

Monitoring

Although monitoring was not done for this project, monitoring should be done by flying at low altitudes to increase the resolution of the pictures in order to determine if germination and plant establishment is achieved and the resultant extent of vegetation cover. In this study area, the ideal time to perform monitoring will depend on when the dispersed seeds typically germinate.

Table 8.1 - Species sown the 10th October 2015

Scientific Name	Common Name	% Mix*	Growth Form	Ecological Function
Avena sativa	Oat	45	Herbaceous grass	Provides carbon, food, plant cover.
Vicia spp.	Vetches	25	Herbaceous legumes	Nitrogen fixation, food and shelter, seed and soil protection
Clematis vitalba	Old-man's beard	5	Vine	Long flowering; attracts biodiversity
Colutea arborescens	Bladder senna	5	Small shrub	Perennial legume with nitrogen fixation capacity
Viburnum tinus	Laurus	5	Tall shrub	Bird food, protects arboreal species
Juniperus oxycedrus	Juniper	5	Tall shrub	Bird food, protects arboreal species, construction material
Cerationia siliqua	Carob	5	Tree	Improves soil, carbon fixation, food
Pistacia lentiscus	Mastic	5	Small tree	Protection and food for birds and other fauna

** Percentage of seeds of each species*

CONCLUSIONS

Sowing is not a hardware problem anymore

Aerial seeding using low-cost, DIY UAVs is no longer limited by hardware. The technologies of multirotor UAVs have been tested and improved considerably over recent years, making such vehicles both more controllable and affordable. The other main factor increasing the feasibility of UAV-seeding is availability of seed-release systems. Open-source hardware and software are creating new opportunities for ecological management and green activism.

Two strategies of aerial seeding with UAVs

We identified two strategies for aerial seeding, using UAVs: i) indiscriminate vs. ii) precision sowing. Indiscriminate sowing over large areas does not need detailed pre-restoration surveys, but many seeds will fall into unsuitable micro-habitats, so seed germination would likely be low and seedling mortality high. To compensate for these high losses, the numbers of seeds sown per unit area could be increased, provided seed supply is sufficient. Conversely, precision sowing can increase seedling establishment rates and so fewer seeds need to be dropped. However, this approach requires detailed knowledge of microhabitats and detailed mapping and research.

Optimization of aerial sowing missions

UAVs can release seeds at very high rates and can move up to 60 km/h. In order to increase the flight time and capacity of the payload of seeds, UAV batteries must be lightweight. Ideal seed sowing strategies would involve short, fast flights, avoiding long flights with heavy payloads.

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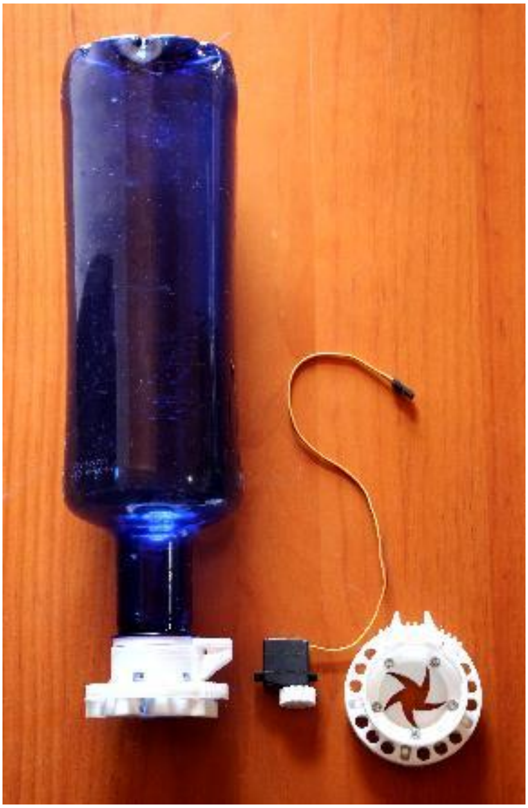

Figure 7.6 – Controlled by mobile phones with open-source software and constructed from open-source hardware, with biodegradable wooden frames, "flones" are inexpensive and easily repaired. Thus, they are ideal UAVs for citizen-based ecological actions.

Figure 7.7 - 3D-printed seed-release system

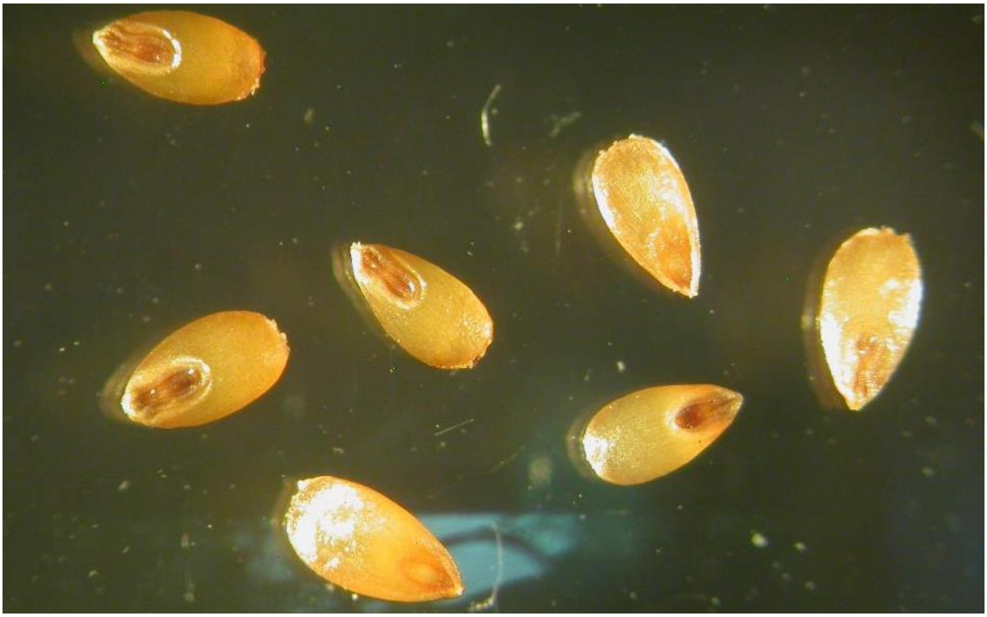

Figure 8.1 - Australian grass seed which are the subject of significant seed-enablement research

Figure 8.2 - Uncoated, coated and pelleted seed

Chapter 8

SMART SEED FOR AUTOMATED FOREST RESTORATION

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ABSTRACT

Aerial seeding may be an effective way to restore forest ecosystems on inaccessible or remote sites; it has been used for almost 80 years in agriculture and now is a widespread practice for post-wildfire revegetation in the US, to reduce soil erosion. The main advantage is rapid seed delivery over large areas, but its use has been limited by high costs, technical limitations, seed wastage, lack of precision and unpredictable success rates. Furthermore, aircraft have rarely been used to deliver the multi-species mixtures of native forest tree species that are required for ecosystem restoration, particularly in the tropics. Recent technological improvements in unmanned aerial vehicles (UAV. i.e., "drones") present new opportunities for cost-effective restoration in remote areas. A re-evaluation of existing aerial sowing technologies, combined with new approaches, currently under development, is therefore timely, to increase the effectiveness of drone-based seed delivery systems.

The development of seed-enablement technologies (SET), such as seed priming and coating could greatly improve the success of aerial seeding of native forest tree seeds by drones. If correctly applied to native seeds, SET could help overcome some of the main factors that limit seedling recruitment, e.g., seed predation, suboptimal edaphic and microclimatic conditions, biotic/abiotic stresses and competition from surrounding plants. This review, focuses on currently available solutions, and outlines the research paths that could lead to the cost-effective use of SET for drone-based forest restoration.

Key words: aerial seeding, restoration, coating, pelleting, darts, drones.

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INTRODUCTION

Ecological restoration is a complex process that requires evaluation of multiple biotic and abiotic variables and integration with local, social and economic frameworks. However, the most important step towards the restoration of a functional ecosystem, is the successful establishment of the plant community.

Revegetation is performed through the return of topsoil, direct seeding, or by planting seedlings or plants (RUIZ-JAEN & MITCHELL AIDE, 2005). The latter is a popular option, because of high survival rates and immediate impact (COMMANDER et al., 2013). On the downside, cultivation, transportation and planting increase the cost of plants and such an approach might not be economically feasible for large-scale projects, particularly in remote, inaccessible areas.

Seeding could be a valid and more cost-effective alternative to tree planting. However, conversion of seeds into established plants is usually low and lack of seed availability, especially in large quantities, may be a limiting factor (WIJDEVEN & KUZEE, 2000; BROADHURST et al., 2008). Consequently, native seeds have rarely been employed in aerial seeding and some of the non-native species that have been used have become invasive, with serious consequences for conservation (e.g., Leucaena leucocephala in Pacific islands).

Seed banks and seed producers are expected to scale-up production to match restoration demands (MERRITT & DIXON, 2011), but to significantly increase seed germination and seedling establishment, advanced seed-enablement technologies (SET), especially seed coating, must be employed. In agriculture, most of these technologies were developed to increase the seed quality of crops, vegetables, turf grasses and fodder plants. Expected establishment rates for these varieties is usually higher than 80% (THE COUNCIL OF EUROPEAN ECONOMIC COMMUNITY, 1966).

Such technologies have been partially applied to aerial seeding, especially to improve ballistic performance, carry substances that reduce attacks by pests and seed-predators (NATIONAL RESEARCH COUNCIL, 1981) and provide inocula of beneficial micro-organisms (BROOKE et al., 1992). However, the potential advantages of seed treatments far exceed current applications. Germination promoters and compounds that induce stress resistance or improve soil-seed interactions could all be included in the treatments. The customization of such solutions to native species could enhance seed germination and recruitment and therefore significantly improve aerial restoration effectiveness and underpin the development of automated forest restoration.

AERIAL SEEDING

The practice of broadcasting seeds from aircrafts has been used for almost 80 years. The first aerial seeding was performed in 1926, in Hawaii, to recover large areas of burned tropical forest. During World War II, the USA alone produced almost 300.000 aircraft that resulted in a surplus of aircraft when hostilities ended (Parker, 2013). Some of them were modified and used for aerial seeding, especially in the Pacific Islands, which had been heavily bombarded throughout the war (National Research Council, 1981).

During the 1950’s, the introduction of the treatment of seeds with pesticides greatly increased seedling establishment, such that more than a million hectares of mostly coniferous forest were established, within 30 years. At that time, Canada, Australia and New Zealand also started aerial seeding programs and developed protocols for different forest types (National Research Council, 1981). However, arguably the widest employment of this technology has been in China. Between 1949 and 1993, aircraft were used to seed more than 17 million ha, resulting in 8 million ha of successful re-afforestation (Nuyun & Jingchun, 1995). In 2012 alone, aerial seeding was performed over 136,400 ha in China (Xiao et al., 2015). The approach achieved impressive results primarily through the rapid delivery of large quantities of seeds over large and otherwise inaccessible areas.

The main goal of aerial seeding projects has been the re-establishment of particular ecosystem services, rather than the reconstruction of viable, resistant and resilient ecosystems reflective of biodiverse reference communities. Therefore, according to the International Primer on Ecological Restoration (Society for Ecological Restoration International Science & Policy Working Group, 2004), such projects cannot be considered as ecological restoration. For example, post-wildfire aerial seeding in the USA aims to rapidly and effectively achieve vegetation cover on burnt areas, to limit large-scale soil erosion, flooding and downstream sedimentation, especially near wildland-urban boundaries (Beyers, 2004). Moreover, rapid re-establishment of aerially seeded grasses limits the invasion of ruderal harmful weeds after fire (Pyke et al., 2013).

Species selection

Non-native species have often been used for aerial seeding, usually because their seeds are cheaper and easier to obtain than those of native species. In some cases, introduced species have been replaced by natives (Greipsson & El-Mayas, 1999), but usually competition negatively affects native species re-establishment. In the past, very little attention was given to the selection of species and the origin of the plant material. Post-WWII aerial reforestation of Pacific Islands was done mainly with the legume Leucaena leucocephala, non-native to all of the islands where it was sown (it comes from S. America). It was considered a very promising plant with potential economic interest (National Academy of Sciences (U.S.), 1977) but, it rapidly became invasive, covering most of the available area, severely disrupting indigenous vegetation and threatening the survival of many rare, endemic plant species (Pacific Island Ecosystems at Risk, 1999). The IUCN lists it among top 100 “world’s worst invasive alien species”. Focusing solely on functional outcomes and short-term economic gain can thus have serious negative consequences on long-term ecosystem health and ecological trajectory that may be costly to correct. Therefore, it is crucial that local indigenous species are employed to the greatest possible extent, to avoid such problem (Society for Ecological Restoration International Science & Policy Working Group, 2004).

Soil

Soil conditions, at the moment of sowing, play a critical role in determining the success of seed-based restoration (Liu et al., 2010). Barren land does not provide the protection of vegetated areas. Therefore, the seeds are more likely to be exposed to climatic extremes. If broadcasted over unprepared soil, seeds could be displaced by water runoff and wind. The absence of physical protection, that could be provided by burial, exposes the seeds to intense sunlight, extreme cold or heat and desiccation, all of which can severely reduce viability. Furthermore, broadcasted seeds might be more exposed to predation by insects, rodents and birds (Turner et al., 2006). On the other hand, if seeded over dense vegetation, seeds might become trapped in the canopy and fail to penetrate to the soil surface. If germination does occur, under such circumstances, competition for resources with established plants will reduce survival and growth.

Seedlings and seed bombs

To overcome the problems of on-site germination, seedlings, contained within aerodynamic projectiles, have been dropped from aircraft (John Walters, 1972). Some of these seedling containers for aerial delivery have been patented (Agnagostou, 1966; Walter & Garthsore, 1973; Arnold, 1982; Gordon, 1982) but, the logistics required to protect growing seedlings adds complexity to the already-challenging process of aerial delivery. Therefore, aerial reforestation using only seeds is much more common (Wood, 2000).

Wood (1981) described an economic, degradable, cone-shaped container for aerial seed deliver, named SCAD (seed containing aerial dart). The aerodynamics of SCAD, its delivery system, soil penetration, seed distribution (Wood, 1984) and the composition of a growth medium, added to it (Scarratt, 1984; Lennox & Lumis, 1987) were all investigated intensively. If correctly employed, SCAD buries seeds to the optimum depth and the growth medium, provides emerging seedlings with all the nutrients, moisture and protection they need during early development.

Dart for drones

SCAD represents an interesting starting point for development of containers suitable for drone-based restoration. However, locally available and inexpensive materials (paper, leaves etc.), the composition of the growth media and delivery mechanisms must all be evaluated. A similar concept, “seed bombs”, is currently under evaluation for large-scale deployment (www.biocarbonengineering.com/). In this case, seeds and a hydrogel are contained within a biodegradable plastic bullet-shaped projectile that is shot from UAVs by a specially designed air gun.

Whether the delivery system is reliant on gravity or compressed air, it is critical to modulate the speed on impact, in order that the seed is delivered to the optimal depth. The shooting force or height of release must therefore be adjusted in response to measurements of soil hardness and moisture level.

The interaction of geomorphological and climatic features also affects seeding outcomes. For example, sowing on steep hillsides increases the likelihood that seeds or seed darts will be washed away by heavy rain or moved down-hill to undesirable locations. Moreover, if the soil is too compacted, the container may break or bounce, regardless of the bomb shape and impact force. It is therefore crucial to evaluate soil conditions and confine aerial seeding to those periods when the soil is soft enough to allow sufficient penetration by the seed projectiles (usually the rainy season).

On steep slopes and compacted soils, hydroseeding has been trialled, whereby a slurry mix of seeds, fertilizer, mulch and polymeric tackifier is used to provide adherence to the inclined surface (De Oña et al., 2011). The mass and volume of the mix, related to the number of seeds, makes this system very unlikely to be functional in aerial seeding, especially using drones, but the range of binding polymers and hydrogels could be directly applied to seeds or containers providing substrate adherence.

Equipment and seeding rate

Aerial seeding has been performed with both airplanes and helicopters. Planes are cheaper, can carry bigger seed loads and cover wider areas more quickly than helicopters. They are more efficient for seeding large and relatively even surfaces, while helicopters can deliver seeds with greater precision even in mountainous areas that are inaccessible to planes, but at substantially greater cost (HODGSON & MCGHEE, 1992). Both types of aircraft require highly trained and skilled personnel and there are always risks for pilots, flying small aircraft at low altitudes over wild, remote and sometimes climatically adverse areas. Many of these problems could be resolved by using unmanned aerial vehicles instead.

Seed delivery devices have been developed since the early days of aerial sowing from rudimentary hoppers, with little control of seed rate, to more efficient gravity- or power-driven slingers that enable a constant rate of seed output (HODGSON & MCGHEE, 1992). The correct seeding rate is essential, to avoid under- or over-seeding resulting in insufficient coverage or seed wastage and competition respectively.

In 1982, Régnière described a probabilistic model that related plant density, soil preparation and aerial seeding rate of Pinus banksiana. Unfortunately, its applicability for restoration is limited, because it does not take into account variability in seed deposition and site characteristics, but it could represent a good starting point for developing more complex tools, to assist practitioners in planning aerial seeding.

UAV seeding equipment

Recently UAVs have become more accessible, reliable and affordable, offering the possibility of employing drones for aerial seeding. With current technologies, the main issues are limited payload sizes and flight times. The use of unmanned helium or hot air balloons could represent a solution to these problems, but high costs, problematic control and manoeuvrability and the impossibility of flight under forest canopies considerably limit their use.

Various delivery mechanisms have been discussed at the first Automated Forrest Restoration workshop held in Chiang Mai, Thailand in 2015 and some practical solutions were demonstrated using drone “dart bombing” in the Upper Mae Sa Valley. The two systems proposed, rely on either gravity or propulsion, especially compressed air. The benefit of “shooting” seeds or seed bombs into the soil with air guns is greater seeding precision, compared with gravity-based systems, but on the downside a gun adds weight to the payload and consumes battery power, which could otherwise be used to lift more seeds or enable longer flight times.

Alternatively, a propelled seed delivery system could allow drones to land on a designated seeding spot and inject seeds into the soil to the desired depth, for maximum accuracy. Seed burial reduces both seed predation and desiccation.

SEED-ENABLEMENT TECHNOLOGIES (SET)

SET aim to increase seedling emergence, persistence and yield, by increasing germination uniformity and vigour, across a range of field and storage conditions. They include quality optimization, germination stimulants, seed priming, coating and other novel seed treatments, all aimed at improving seed germinability and increasing mechanization of seed handling. These approaches have not been systematically researched for restoration practice, but their development for the restoration industry offers great potential to increase seed performance substantially.

Seed priming

Priming involves subjecting seeds to pre-sowing, controlled. hydration (Fig. 8.1), sufficient to permit pre-emergence metabolic activity but insufficient to allow radicle emergence, followed by re-drying for ease of handling and sowing (KHAN, 1992). Seed priming promotes more rapid and synchronous seed germination of many horticultural and agricultural species (BROCKLEHURST & DEARMAN, 1983; BRADFORD, 1986; KHAN, 1992; HARRIS et al., 2001). Whilst published studies on the effects of priming on germination of wild species, are limited, such techniques are well established in agricultural and horticultural enterprises and clearly provide promise for the restoration industry and could be beneficial with little additional weight or bulking problems for drone-based delivery systems.

Seed Coatings

Seed coating consists of creating an artificial external coat around single or agglomerated seeds using polymers, inert powders and active compounds. It improves seed handling through physical modification (Fig. 8.2) and protects seeds from predation and diseases by delivering specific treatments. These techniques are effective in reducing rodent and bird predation of crop seeds and limit the effects of seed-borne diseases and fungi (SCOTT, 1989).

Large-scale, commercial use of coating began in Europe in the 1960's, to enhance precision-sowing for the European greenhouse industry. When California outlawed the short-handled hoe in the mid 1970's, the use of coated seed for precision field seeders increased significantly (KAUFMAN, 1991; HILL, 1999), along with the research effort by private companies, to gain a competitive advantage in this emerging market. This practice has proven to be so efficient that nowadays most agricultural and horticultural seeds are coated or pelleted. This technology is rapidly spreading in developing countries and the global market for coating materials is expected to rise to almost 1.5 billion USD in 2019. (RESEARCH & MARKET, 2014).

The advantages provided, by physically modifying seeds and delivering beneficial active compounds have driven the increased application of seed coating techniques. Physical alteration of seed shape, size and weight enable standard dimensions for uneven and otherwise hardly manageable seeds resulting in more efficient mechanical sowing with optimal seed spacing; ultimately reducing seed wastage (TAYLOR & HARMAN, 1990).

Seed coating has also been used as a carrier for active compounds that help overcome some of the most common problems of seed storage, sowing and emergence. The most commonly used compounds are pesticides, insecticides, fungicides, nutrients and inoculae of beneficial symbiotic microbes. The application of these substances, directly to seeds, is gradually replacing the practice of spraying crop and vegetable fields with expensive and less effective treatments and it is consequently reducing levels of potentially harmful compounds in the environment. Compared to foliar spray or in-furrow delivery, the ability to have precision targeting of a treatment reduces the application rate per unit area of an agent by 90-99.5% reducing the risk of impacting non-target organisms.

On the other hand, some of the most effective insecticides, used in seed coatings – neonicotinoids - are being re-evaluated in the EU as these compounds are considered to be detrimental to honeybees and may be partially responsible for widespread colony collapse disorder (RUNDLÖF et al., 2015).

The seed coating industry and research

The largest global seed companies have developed research programs dedicated to improving these technologies and gain commercial advantages over their competitors. Therefore, most of the technological know-how is either patented or are trade secrets (JAMIESON, 2008). Such restricted access to high-value knowledge could impede scientific research. In most of the studies where coating and pelleting were tested, the treatment was outsourced to external companies and the methods were not disclosed. This lack of practical knowledge has probably affected the number of studies carried out on this technology.

Coating nomenclature

Coating techniques are categorized by size and weight of the externally applied material. Although there is no universally recognized nomenclature standard, most seed technology companies define coating of increasing thicknesses into categories such as film-coating, encrusting and pelleting respectively.

A seed is considered coated when its surface is covered by coating agents and its weight gain is usually less than 20%. For greater weight increases, treatments are classified as encrusting, as long as the original shape of the seed remains. Once the shape becomes spherical, the seed is considered pelleted. Seed coating and encrusting are on a weight gain basis, whereas pellets are measured by diameter increments (Fig. 8.2).

Seed-coating equipment

The equipment employed closely resembles that used for coating in the pharmaceutical and food industries. The first seed coating machines were rotating pans based on a model originally patented in the 19th century (WILLIAM E. UPJOHN 1885) for making medicinal pills. Since then, more than 20 patents on seed coating machines have been lodged but, according to GREGG & BILLUPS (2010), the most widely used machines today, along with the rotating pan, are based on rotor-stator (Fig. 8.3) and fluidized bed technologies. For projects with low budgets and limited access to these technologies, affordable alternatives have been described in although compound delivery precision, coat/pellet quality and large-scale replicability could be limited. The most commonly employed alternative equipment are cement mixers (HATHCOCK et al., 1984; HODGSON & MCGHEE, 1992), bags that are shaken with seeds (AVELAR et al., 2012) and manual application of materials onto seeds (CORLETT et al., 2014).

Seed-coating materials

The range of materials used for these techniques can be sorted into three main categories: binders, fillers and active components.

Binders are usually polymers that act as glues, that stick the fillers and active components to the seed. They are delivered as aqueous solutions, directly poured on the seeds, via atomizer or spray nozzles. Their binding effect becomes prominent after drying. The most common binders used are: gum arabic, gelatine, starch, methyl cellulose, polyvinyl alcohol, polyoxyethylene glycol-based waxes and carboxymethyl cellulose (Taylor & Harman, 1990).

Fillers are fine powders of inert materials. Their main goal is to increase coat thickness without interfering with seed physiological activities or the properties of active compounds. They must be non-toxic and chemically inactive and allow for gas exchange and water uptake. The most commonly reported fillers are bentonite, calcium carbonate, diatomaceous earth and talc. When compounds, potentially detrimental to seeds are applied, the filler acts as a physical buffer to avoid direct contact between the treatment and the seed (Scott, 1989).

Seed coating technologies, especially pelleting, would be particularly useful for UAV seeding, because pellets could be dropped directly without the need of further seed containment or ballast material, although studies comparing the efficiencies of the pellet against seed darts are yet to be performed.

While fillers and powders provide physical structure, the most useful advantages of this technology reside in the active substances. The most common treatments delivered via seed coatings are fungicidal, insecticidal, predator repellent and disease control.

Coatings for AFR

Various active compounds can be used in coatings, but most are proprietary, owned by agrochemical companies. Recently, several studies have focused on evaluating alternative, organic and locally available materials to deliver seed protection and enablement. One of the most interesting recent innovations is chitosan, a compound derived from the crushed shells of crustaceans. It has proven to be an effective environmentally friendly alternative to conventional pesticides (Zeng & Shi, 2009; Zeng et al., 2012). Different local materials. ranging from gums, resins, crushed leaves and other plant materials have so far yielded mixed results. However, they are well worth exploring as positive results could have a significant impact on community-based forest restoration projects where funding is limited. For example, chilies, wood vinegar, coffee grounds and cat urine/litter have all been proposed for evaluation as seed-predator repellents.

Biochar and mycorrhiza coatings

Over the past decade, biochar has attracted considerable attention from the scientific community, following its widespread use in horticulture. It is a charcoal-based product, obtained by combusting plant material in a low-oxygen environment.

Some studies have shown that biochar retains water and nutrients and protects seeds from pathogens, but results are inconsistent and some negative effects on plant establishment and yield have been reported (CERNANSKY, 2015). Although its efficacy has yet to be confirmed, biochar as a seed-coating amendment may protect seeds from herbicides. It has already been evaluated for seed pelleting, but it has exhibited neutral or negative effects on seed germination and plant growth (WILLIAMS et al., 2016). Despite some uncertainty, this product is worthy of further evaluation such as examining different sources of biochars and its impact on different species and under various conditions. Some local initiatives, like the "biochar seed ball" in Kenya (www.facebook.com/BiocharSeedballs/), are evaluating the effectiveness of this technique on forest species (Fig. 8.4).

Integration of beneficial microorganisms, within coating materials includes the use of rhizobia to enhance root nodulation in legumes to facilitate nitrogen fixation. Recently COLLA et al. (2015) demonstrated that coating wheat seeds with mycorrhizal fungi increases growth (up to 60%), and yield (25%). A similar approach with forest tree species, in degraded areas where the soil fungus community is diminished, could potentially deliver great benefits.

Seed coatings for restoration

Despite many advantages, seed coating technologies have rarely been used for restoration, probably due to technical limitations and the high initial cost of equipment, materials and the need for primary research when using native seed. Some attempts have been made in the Qinghai–Tibetan Plateau, China (LIU et al., 2010), southwest Australia (TURNER et al., 2006) and the Pacific northwest of the USA (MADSEN et al., 2012, 2013), but with mixed results. Seed coating and pelleting have already been used in several aerial seeding projects, mostly to improve the ballistic performance of small, light seeds (SCOTT, 1989) and incorporate predator deterrent substances and inoculae of *Rhizobium* (BROOKE et al., 1992). However, coating and pelleting are usually performed with obsolete coating equipment and techniques and are considered as costly and time-consuming (HODGSON & MCGHEE, 1992).

Moreover, the variable physical, morphological and physiological diversity of native seed characteristics, along with the complexity and often adverse environmental and soil conditions at restoration sites require major research effort on a global scale, to customize available technologies to native forest tree species.

A crucial development in these technologies is the employment of seed germination promoters and stress-resistance-inducing compounds. Salicylic acid (aspirin) and karrikins (plant growth regulators found in the smoke of burning plant material) have already proven to be effective plant growth promoting adjuvants. The former enhances seedling survival under biotic and abiotic stress conditions (Senaratna et al., 2000; Stevens et al., 2006), while the latter improves germination rate and synchrony in many species (Dixon et al., 2009). Guan et al. (2014, 2015) demonstrated drought and chill stress resistance in corn seeds, when salicylic acid was added to a seed coating. The best results were obtained when the coat was enriched with a superabsorbent hydrogel which releases the treatment, in this case, salicylic acid, when activated by particular moisture and temperature conditions. The integration of hydrogels and or absorbent fillers also creates favourable microclimatic conditions around seeds, which enhance germination and protect emerging seedlings from extreme temperatures and drought.

CONCLUSIONS

Aerial seeding combined with seed-enhancement have rarely been used for forest restoration. Drones could feasibly replace piloted aircraft to increase the cost-effectiveness of revegetation, particularly on inaccessible sites. Aerial seeding technologies, such as seed darts, have already been developed and could be adopted and customized for drone-based deployment. SET could also deliver a great boost to automated forest restoration, particularly seed coating and pelleting that maximises seed germination and seedling performance. A wide variety of predator deterrents, protectants, nutrients and germination stimulants are described in the literature, including several low-cost, locally available and organic compounds. Future use of seed enablement and drone-based technologies will rely on developing combinations of seeding equipment, seed delivery devices, growth matrices, and coating materials that are tested under field conditions. Ultimately advances in automated seeding will require a multidisciplinary approach and may rely on technological advances that will provide solutions not yet available if restoration seeding is to move from the “stone age to the drone age” (Elliott, 2015).

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Figure 8.3 – Seed-coating equipment, lab-scale rotary coater on the left, rotating pan on the right.

Figure 8.4 – *Acacia* seed balls, made with biochar, in Kenya

Figure 9.1 - ***Ageratina adenophora*** **(crofton weed) supresses growth of tree seedlings over vast areas of upland northern Thailand. It is one of many invasive exotic weeds that threaten the success of forest restoration. Insert: the rust fungus,** ***Baeodrum eupatorii*****, is a potential biological control agent (Photo courtesy of Dr. Louise Morin)**

Figure 9.2 - ***Pteridium esculentum*** **(Austral bracken fern) can be controlled by herbicides, but several applications may be needed.**

Chapter 9

INNOVATION AND ROBOTICS IN FORESTRY WEED MANAGEMENT

Bruce A. Auld[1]

ABSTRACT

Traditional and established methods of weed management are outlined, from hand-weeding, to the use of herbicides and biological control. Recent new developments in detection and control methods are introduced, including robotics, microwaves and lasers. Potential roles for the various techniques and management options for forest restoration are then discussed. Robotics could play an important role in accurately detecting and controlling weeds. Low-volume herbicide application, by unmanned aerial vehicles (UAVs) appears particularly suitable. However, integrated weed management, using several methods will probably be required. This should include selection of the most competitive tree species for initial restoration plantings and screening desired tree species for tolerance to herbicides.

***Key words*:** allelopathy, application, detection, drones, herbicides, mulches, resistance, robotics, tolerance, UAVs

INTRODUCTION

Native forests are under threat from continued exploitation with a net reduction in coverage of some one billion hectares worldwide, since the early 1700's. Although restoration is progressing well in some regions (BLASER & GREGSON, 2013), weeds are a major constraint to forest recovery (VASIC et al., 2012). Traditional methods of weed control, in most of the areas requiring forest restoration, are labour-intensive and are consequently becoming increasingly expensive. Moreover, the steep and rugged terrain of many forest restoration sites renders them inaccessible by wheeled vehicles.

In this paper, I review established methods of weed control (Fig. 9.5) and introduce recent developments, including the use of robotics. The potential use of various techniques is then discussed in relation to forestry, particularly forest restoration in northern Thailand.

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ESTABLISHED METHODS OF WEED CONTROL

Chemical

Chemical weed control has been practised since the late 1800's. Herbicides (not 'weed killers', as they do not necessarily discriminate) come in a variety of forms and chemical compositions. They may or may not be selective and the period of their activity varies widely. Since the late 1940's, selective herbicides have been available and there are now many herbicides, usually categorized by their chemical mode of action.

Selective herbicides

Many herbicides are selective in that they affect either grasses (e.g., dalapon) or broad-leaved plants (e.g., 2,4-D). Amongst the latter, some are more effective on woody weeds (e.g., 2,4,5-T). Others have been developed for high selectivity within particular crops, e.g., chlorsulfuron to kill grass weeds (*Lolium* spp.) in wheat (a grass). Some herbicides, with the same active ingredient, may be available in different formulations for different target weeds. For instance, 2,4-D is formulated as an amine salt, a sodium salt or an ester; the latter being more volatile than the former two; the sodium salt can also be applied as a powder.

Non- selective herbicides

Many non-selective herbicides kill a wide range of plant species. Their lengths of residual activity in the soil vary considerably. These range from short-term (e.g., diquat (fast acting) and glyphosate (slower acting)) to longer term (e.g., bromacil). The latter are used in established plantations and industrial situations; those with low water solubility are the safest (e.g., oxyfluorfen).

Application

Herbicides can be applied in a various way; some as granules and others as liquid sprays. Concentrations of active ingredients, spray volume, droplet size (e.g., Creech et al., 2015) and adjuvants, such as wetting agents (Gaskin et al., 2013) can all influence treatment efficacy. With large (c. 300 µm diameter) droplets evaporation and drift are reduced, but canopy penetration is also less than with small droplets (c. 100 µm diameter). Halving droplet diameter increases the number of droplets by x 8, for any given volume of spray. Hydraulic sprayers control droplet size by nozzle type and pressure: low pressure and large nozzles produce large droplets and the converse produce small ones. Controlled droplet application (CDA) sprayers control droplet size by rotational speed (Fig. 9.7). Such sprayers are useful for applying low volumes and may be adaptable for use on UAVs or drones (Fig. 9.4). Adding dyes to herbicides is useful, to show where herbicide has been applied and consequently avoids spraying the same plants more than once.

Shields around sprayers can protect adjacent plants from herbicides. Liquid formulations may also be applied by hand (e.g., cuts on the stems of large woody weeds) and via wick-wipers (e.g., *www.wickwiper.com*). Some woody species can be controlled by basal bark sprays. Another technique is to use very high concentrations of translocatable herbicide applied in small volumes, sometimes referred as the splatter-gun technique, to control woody weeds such as lantana (*Lantana* spp.). This could be adapted for drone-applied herbicides with limited payload capacity although existing splatter-gun applicators are gas-powered.

Weather conditions can influence herbicide efficacy. A rain-free period of at least a few hours is required for foliar applied sprays; the temperature should be below 28˚C and wind speeds of 2 to 10 km/hr are optimal. Spraying should be avoided when an inversion layer is present (Fig. 9.4), because spray drift may remain concentrated in low clouds and travel long distances.

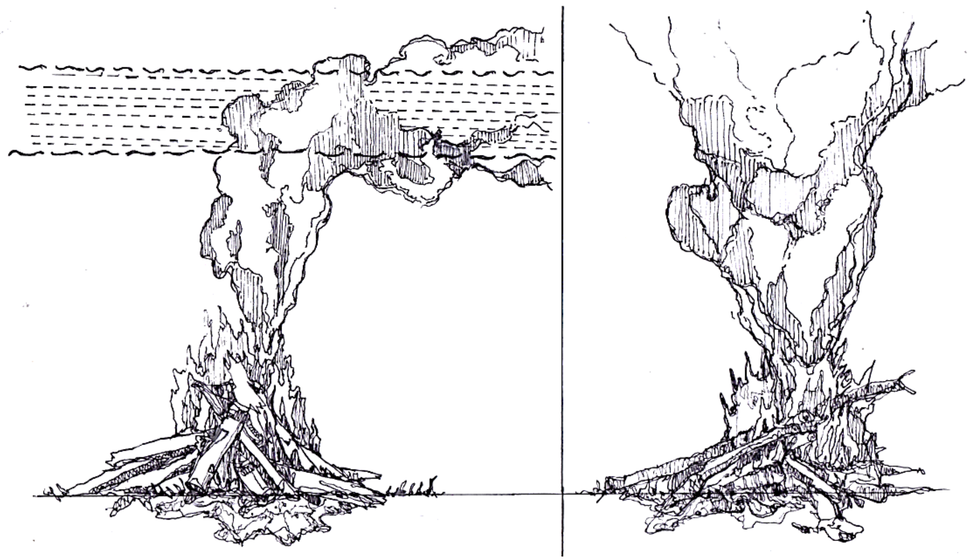

Figure 9.4 – Smoke moving horizontally (left) indicates an inversion layer cf. right

Figure 9.3 – DJI's Agras MG-1S is an eight-rotor craft spanning 1.47 m with a 10-litre liquid capacity. It is priced at US$15,000 (Photo: DJI)

Herbicide resistance

The continued use of one or a few herbicides, with the same chemical mode of action on the same site, will eventually induce herbicide resistance in some species and consequently bring about changes in the composition of the target vegetation. However, herbicide resistance in desired plant species introduces the possibility of their use with that herbicide as a management option. Consequently, several commercial, herbicide-resistant, crop cultivars have been bred. Some plant species, although not entirely resistant to some herbicides, may display degrees of natural tolerance to those herbicides; traits that could prove very useful for selective weed control.

Physical

Hand weeding

Although still practised in developing countries and for within-row weeds in some developed agricultures, labour costs generally make hand weeding too expensive for broad-scale agriculture and forestry.

Ploughing

Ploughing, using mechanical or animal power, has the advantage of removing weeds and preparing a seed-bed. In steep terrain (slopes >20˚), the use of wheeled machinery is unsafe and crawler traction machines are required. However, these are unlikely to be employed in many areas because of access problems, damage to useful plants and soil compaction.

Mowing

Mowing or slashing can prevent weeds flowering and seeding and reduce their underground storage reserves. Height and frequency of mowing can be varied to obtain desired results, but mowing alone rarely kills established perennial weeds.

Burning

Broad-scale burning is generally non-selective and although apparently cheap, supplementary costs are involved in preparing fire breaks, monitoring fires and having fire-fighting equipment on standby. The use of fire is very dependent on the fuel load and condition, as well as on weather conditions. Moreover, few vegetation types, such *Eucalyptus* forests in Australia, recover from fire via epicormic buds along their stem.

Use of heat: water / steam / flame

The use of heat is a non-selective method of weed management, suitable for control of annual plants or the suppression of perennials. It requires a portable source of heat (HOYLE et al., 2012). Flame applications may be labour intensive (GHANTOUS et al., 2012) but can utilize all-terrain-vehicle-mounted flamers (KNEZEVIC et al., 2014). Obviously, there will be many situations where burning is too risky to contemplate.

Mulches: plastic, clear and opaque; biodegradable materials

Plastic sheeting has been used for soil solarisation (heating) to control soil borne diseases and also to suppress weed growth (ELMORE, 1991; STAPLETON, 1991). Black 'weed mat' polymer materials, which allow penetration of water but not sunlight, are now widely used in horticultural plantings to surround planted species and protect them from weed interference. They may be held in place by organic materials. Biodegradable organic waste (JOHNSON et al., 2014) produced, for instance, by mowing or slashing weeds, can also be used directly to suppress weeds, retain soil moisture and buffer soil temperature. A biodegradable matting made from linseed straw, has recently been developed in Australia (MIAO et al., 2013). It degrades after a few months. In New Zealand, another biodegradable matting, EcoCover®, is produced from waste paper (http://ecocover).

Flooding

Flooding is used to control weeds in rice and in rice-sugarcane intercropping systems.

Biological

Classical biological control

Classical biological control involves the release of a natural enemy of a specific weed. The biocontrol agent (typically an insect or fungal pathogen) is imported and once established is self-sustaining. A significant aspect of this approach is that the biocontrol agent searches for and finds the target weed. There are many examples of successful biocontrol programs. However, the main limitation is that only one weed species is targeted at a time. Programs are usually aimed at only major weeds, because of the time and resources involved in searching for potential agents before their release and host-range testing. Although biological control agents occasionally attack non-target species, such incidences and their severity are decreasing over time (HINZ et al., 2020).

Inundative biological control

Inundative biocontrol is relatively short-term control achieved by applying high dose rates of an agent (usually fungal spores in a water-based suspension) to a target weed species, creating a short-lived, localised epidemic. The technique, equivalent to having an herbicide specific to one weed species, hence the term bioherbicide (or mycoherbicide), is often used to describe these agents (AULD, HETHERINGTON & SMITH, 2003). Only a small number of these products have been produced, because of several constraints (AULD & MORIN, 1995).

Ecological

Domestic grazing animals

The use of grazing or browsing animals to control weeds is widespread. This technique may require fencing (often solar-powered, portable electrical fencing) to achieve high stocking rates in confined areas, and the provision of water supply points. Goats have been used successfully, particularly for woody weeds and tussock grass control but require careful management. In forestry, such as animals are just as likely to browse on trees as they are to graze on forbs and grasses.

Competitive cultivars

A range of possibilities exist in terms of using crop/tree cultivars with improved competitive ability, planting density and arrangement (a rhomboidal pattern of planting occupies available space best). Interest in cultivars that have allelopathic qualities is increasing.

Cover crops and companion plants

Living mulches, such as annual, leguminous cover-crops may be used to smoother weeds. They can become biological mulches as they senesce. Their sowing times, sowing rates, growth habit and placement, in relation to the desired crop, should always be taken into account. Considerable field experimentation may be required, to establish optimal arrangements.

NEW INNOVATIONS

Detection

Within the last decade, dogs have been trained to detect single plants of newly invading weed species in various environments (e.g., GOODWIN et al., 2010) and, for several years, aerial photography and satellite imagery has enabled delimitation of some widespread species and plant communities. However, the detection of specific weed species, on a scale between these two extremes, has recently been achieved using unmanned robotic vehicles (see below).

Use of air-propelled grits

This is a relatively new innovation that has been used for successful selective control of weeds in crops such as corn, soybeans (Forcella, 2009) and vegetable crops (Wortman, 2014). Grits are produced from various organic sources including corn cobs, walnut shells and bone meal. Following application, these materials all act as mulches and fertilizers. Application of grits requires specialised high-pressure equipment.

Microwaves

Dr Graham Brodie has recently developed a microwave weed controller in Australia (Brodie, 2017). The prototype device is quite successful at controlling a range of weed species and buried weed seeds, but it is far too bulky to be mounted on UAVs.

Lasers

The use of lasers to damage weeds has been suggested for some time (Hoki, 2000). Recent developments with carbon dioxide laser radiation are encouraging, but they are still at the experimental stage (Marx et al., 2012).

Genetically modified crops with herbicide resistance

New cultivars of certain crops, such as soybeans and cotton, have been developed to be resistant to certain herbicides, including glyphosate by genetic engineering. This greatly simplifies weed management in these crops, but such cultivars may encourage the overuse of herbicides, with consequent negative environmental impacts and the development of new herbicide-resistant populations of weed species. Naturally resistant or tolerant species or varieties could also be employed.

Allelopathic crops

Amongst the various cultivars of some crops, such as barley and rice and their ancestors, allelopathic activity (production of plant compounds that inhibit neighbouring competitive plants) is sometimes found. Selection of such varieties would reduce the need for other forms of weed control (Pratley, 2012). Breeding programs and research on allelochemicals and their mode of action may lead to further advances in this field. Some forest tree species, including *Eucalyptus* spp. and *Gmelina* spp. are known to have allelopathic properties, usually via suppression of seed germination.

Robotics

Small unmanned helicopters (Fig. 9.6), such as the Yamaha R-MAX, have been used for several years in Japanese agriculture, especially for sowing and spraying rice. Precision application technology is advancing rapidly in agricultural systems including the development of planting robots (YOUNG et al., 2014).

Detection

Detection and treatment of weeds in crops by light-activated, sensor-controlled, on-ground spraying systems have been progressing (BILLER, 1998; RIAR et al., 2011). Recent advances, using unmanned aerial vehicles (UAVs) flying at low altitudes, have achieved spatial resolutions of 3 pixels per centimetre (TORRES-SANCHEZ et al., 2013; CLEMENTS et al., 2014; GOKTOGAN & SUKKARIEH, 2015). Such a high-resolution allows interpretation using spectral response, colour, texture and the 3-D structure of vegetation, enabling discrimination between plant species (HUNG et al., 2012; 2014) cf. other techniques, which use only one or two of these factors.

Application

UAVs can also carry spraying devices for weed control; moreover, the two activities can be linked through GPS recording of the presence of the target species for subsequent treatment.

FOREST RESTORATION IN NORTHERN THAILAND

Roles for established weed control methods

Non-selective herbicides

These herbicides can be used to prepare an area before tree planting. Non-residual herbicides should be used, to avoid possible subsequent damage to growing trees. Herbicides could be applied as strips or in a checker-board fashion (where trees are to be planted) rather than treating an entire area. Some tree species may display degrees of tolerance to some non-selective herbicides, such as glyphosate, depending on application rates. This could be a useful avenue for research with some simple field-based screening experiments on weeds and trees together.

Selective herbicides

Selective herbicides would be most useful, where the main competing weeds were grasses and graminicides such as fluazifop-p-butyl could be used in these situations.

Ploughing / Slashing

These techniques are likely to be limited by costs and difficult terrain, moreover ploughing may expose soil to erosion. Slashing (or mowing) by hand or machine does have the advantages of reducing competition and providing mulch.

Classical biological control

This approach would be suitable where one weed species was dominant, such as crofton weed, *Ageratina adenophora* (Fig. 9.1). There are some established biocontrol agents for crofton weed in Australia (AULD, 1969) and elsewhere that are only partially effective. However, a recently introduced host specific-rust fungus is proving highly promising in Australia (MORIN, 2015).

Inundative biological control

As for classical biocontrol, this method typically addresses a single weed species and would only have application where one weed was dominant. There has been considerable research on the fungus *Ascochyta pteris* as a potential bioherbicide for bracken fern (*Pteridium esculentum*) (Webb & Lindow, 1987) (Fig. 9.2), but like many potential bioherbicides creating a formulation to overcome dew requirements of the fungus has been a stumbling block to further development.

There may be a role for allelopathic species and/or products derived from them as broad spectrum bioherbicides, but they would need to be selective *i.e.,* not affecting planted trees (see below).

Grazing

The use of grazing animals to reduce weed biomass would depend on their availability, husbandry and the specificity of their grazing behaviour. Access to water and confinement with solar powered electric fencing would probably be required as well as constant surveillance.

Competitive crops / trees

Selection of tree species and varieties for maximum growth rates and other competitive characters should be worthwhile; the influence of provenance may also be important. This work is already in progress as part of the 'framework species' method at Forest Restoration Research Unit at Chiang Mai University.

Companion planting

It may be possible to use cover crops such as hairy vetch (*Vicia villosa*) which could smother weeds, provide some allelopathic activity and add nitrogen to the soil (FUJI, 2003). This would require considerable field experimentation to examine sowing rates as well as the interactions with trees and weeds.

Potential roles for new innovations in weed control

Herbicide resistant tree species

The development of native tree species with herbicide resistant genes would require considerable commercial investment and is unlikely to happen in the short-term. However, as mentioned above, some tree species are likely to have tolerance to some herbicides; for example, leguminous trees to glyphosate, and this would be worthy of further investigation.

Allelopathic tree species

Just as allelopathic varieties of crop plants or their ancestors have been found, some degree of allelopathy could exist in forest tree species and to the wider gene pool by selective breeding.

Allelopathic bioherbicides

The use of allelopathic plants as broad spectrum 'bioherbicides' is worthy of further investigation. Often with this approach, the bulk of material required to produce an effect makes the idea impractical. However, LAOSINWATTANA et al. (2012) have used granules manufactured from leaves of the native allelopathic tree, *Aglaia odorata*, to achieve selective control of weeds in maize in Ratchaburi Province, Thailand. (If an active chemical ingredient is isolated from such a plant and applied as a spray, it becomes an herbicide, like any other.)

Possible roles for robotics

Detection

Detection capacity is improving rapidly (e.g., HUNG et al., 2014). As suggested above, rather than detecting weeds to spray, detecting forest tree species to avoid spraying may be a promising approach.

Planting

There is scope for planting tree seeds and seedlings together with other materials, such as fertilizer and mulches by drones and this is covered in other papers at this workshop.

Application of herbicides and/or other materials

GPS technology and spray control allows accurate application of herbicides in strips, checker-board fashion or some other programmed arrangement, such as avoiding desired trees. The use of low volume and controlled droplet techniques such as spinning disc sprayers (Fig. 9.7) on drones (Fig. 9.3), together with marker dyes, would be particularly useful. Drones could, potentially, also deliver biocontrol agents or carry other weed control devices such as lasers.

CONCLUSIONS

In terms of weed management, robotics can play an important role in weed (or crop) detection, accurate application of herbicides and other materials. Low-volume, controlled-droplet, herbicide applicators, in association with UAVs should be particularly useful. Notwithstanding this, an integrated approach is required, combining several methods to manage weeds and their impacts. Integrated weed management should include selection of the most competitive tree species as framework species. In addition, selecting tree species that are tolerant or resilient to broad-spectrum herbicides is also a promising avenue for research.

Potential tactics in weed management for forest restoration

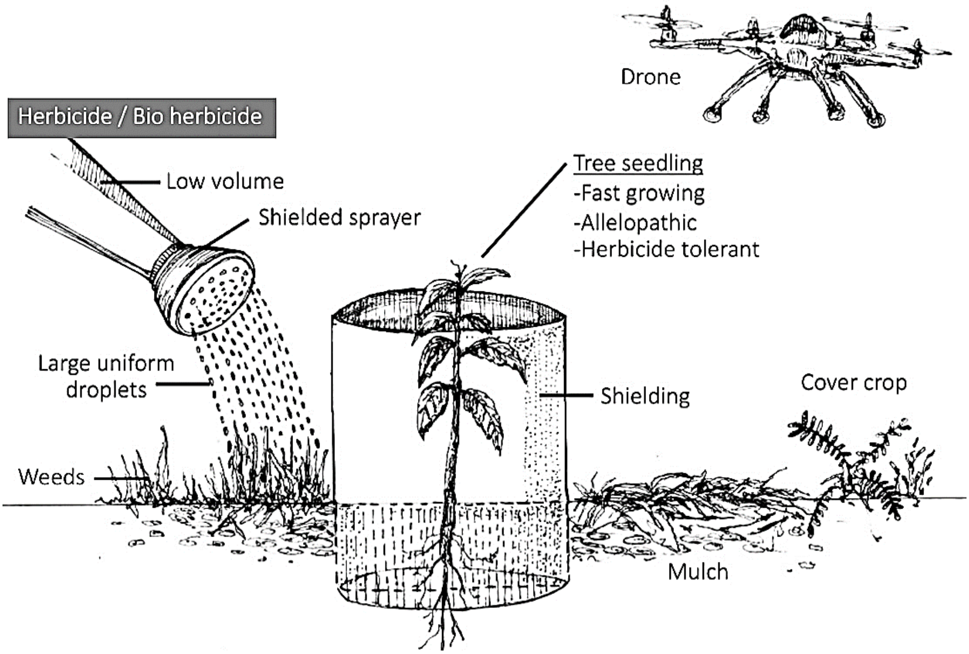

Figure 9.5 - Schematic representation of a variety of approaches to weed management in replanting in forest restoration.

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Figure 9.6 – An auto-piloted mini helicopter, used for weed control

Figure 9.7 - Controlled droplet (spinning disc) nozzles could potentially be used to apply herbicide from on drones. They use low volumes and create large droplets, which would reduce non-target damage.

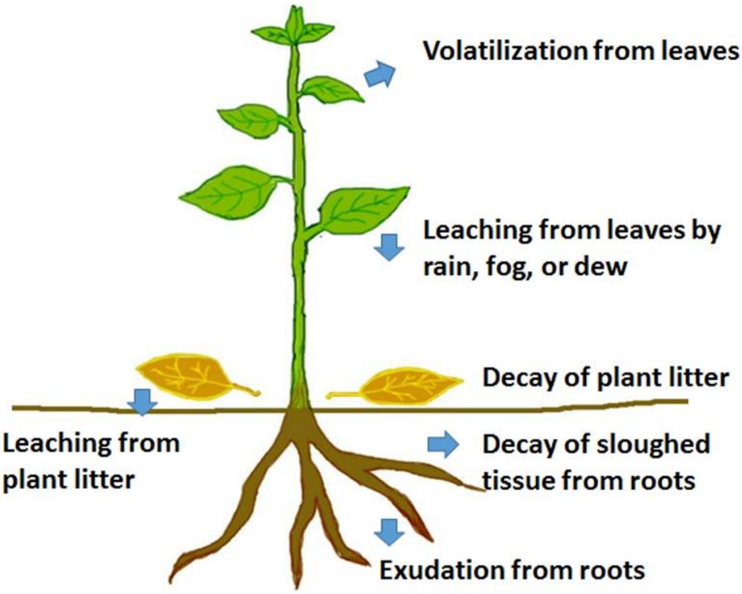

Figure 10.1 - Sources of allelopathic chemicals from plants.

Photo – Stephen Elliott

Figure 10.2 – Allelopathic exclusion of grass by a coppicing *Gmelina arborea* tree, probably due to chemicals leaching from its leaf litter. Note the growth of scandent vines into the grass-free zone by plants rooted outside of it. Could allelopathic chemicals from aggressive pioneer tree species, like *G. arborea*, be used to control weeds during forest restoration? Or would the exclusion of some weed species let others proliferate?

Chapter 10

ALLELOPATHY FOR WEED MANAGEMENT IN FOREST RESTORATION

Suphannika Intanon[1] and Hathai Sangsupan[2]

ABSTRACT

In forest restoration, weeds compete with tree seedlings for water, nutrients, sunlight and space, as well as act as habitat for pests and diseases. Allelopathy - the inhibition of one plant by another - may allow weeds to be controlled without the environmental hazards associated with synthetic herbicides. Allelopathic compounds, or allelochemicals, are released by different plant parts and processes (e.g., flowers, stems, and root exudates, residue decomposition and volatilization). Plants that exhibit these properties have been identified in both natural and agricultural systems. In this chapter, we discuss the potential uses of allelopathy for weed management in forest restoration. This includes the planting of allelopathic tree species, the incorporation of allelopathic plants or weeds into planting sites, and the use of allelochemicals in auto-weeding for automated forest restoration. Auto-weeding, using allelopathy, could be a more environmentally friendly, cost-effective alternative to synthetic herbicides in forestry systems. However, research is required to identify the source and target species of allelo-chemicals, evaluate their effectiveness in the field, and determine the optimal timing, rate, and application methods, for their use.

***Key words*:** allelopathy, allelochemicals, auto-weeding, invasive weed

ALLELOPATHY FOR WEED MANAGEMENT

In forest systems, herbaceous weeds compete with tree seedlings for water, nutrients, sunlight, and growing space. Weeds also provide habitat for pests and disease organisms (ZIMDAHL, 2013). Foresters commonly employ synthetic chemical herbicides to control weeds. However, synthetic herbicides are costly and may be hazardous when used improperly. Synthetic herbicides may cause additional unfore-seen health and environmental consequences, if the chemicals drift to non-target organisms and persist in the environment (ZIMDAHL, 2013). These risks impede their use in sustainable forest restoration.

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"Natural" herbicides, from plant secondary metabolites, represent a promising alternative, although they may have some of the same shortcomings. Secondary metabolites are organic compounds that are produced at the end of biosynthetic pathways. They are therefore not required for plant growth and development. Instead, they aid in plant survivability and fecundity (GUTZEIT & LUDWIG-MÜLLER, 2014). For example, they may attract pollinators or seed dispersing animals, repel herbivores or pathogens or increase tolerance of abiotic stress. Plant secondary metabolites are often multifunctional, providing in an array of biological activities, some of which have been exploited for human use (MACÍAS et al., 2007). Secondary metabolites with allelopathic effects (i.e., allelochemicals) in particular have considerable potential as potential herbicides to control weeds in sustainable forest restoration.

Allelopathy is "the chemical inhibition of one plant by another" (RICE, 1984). Allelochemicals are recognized tools for weed management in both agriculture and forests (CUMMINGS et al. 2012; MACÍAS et al., 2007). Unlike some synthetic herbicides, allelochemicals often have short half-lives and decompose into innocuous organic compounds (DUKE et al., 2000). Allelopathic plants release allelochemicals into the environment by leaching, root exudation and volatilization (Fig.10.1). MACÍAS et al. (2007) provide four conditions to identify allelopathic events. They include i) a plant distribution that cannot be explained by physical or biotic factors, ii) the proximity of allelopathic plants that synthesize and release bioactive chemicals, iii) the presence of appropriate concentrations of allelochemicals in the soil to reach the target and finally, iv) evidence of either detrimental or beneficial effects caused by allelochemical uptake in target plants. In forest restoration, this approach to identifying allelopathic plants can be applied to selecting allelopathic tree species for planting and for determining which allelochemicals might be appropriate for incorporation at the planting site.

Identifying tree species with allelopathic properties

Many weed species are unable to thrive beneath the shade of over-story forest trees. In some cases, however, this inhibition is in part the result of allelopathy by trees, rather than simple competition for light in the understory (BHATT et al., 2010) Exotic weed species may be particularly susceptible to allelopathy from native trees (CUMMINGS et al., 2012). This suggests that native tree species could be used in forest restoration to suppress troublesome exotic weeds.

Certain plant families or genera have been associated with high concentrations or high diversity of secondary metabolites with potential allelopathic effects (SINGH et al., 2003; WINK, 2003). Tree species in the Fabaceae family are associated with nitrogenous defensive compounds (WINK, 2003). For example, CUMMINGS et al., (2012) found that leaf litter from native leguminous tree species in Central America (*Inga punctata*, *Gliricidia septium*, and *Diphysa americana*) had a greater inhibitory effect on the invasive Asian grass, *Saccharum spontaneum*, than non-leguminous trees did. Furthermore, several studies have demonstrated the ability of allelopathic native trees to protect themselves against exotic weeds. HOU et al., (2012) reported that, in a pot experiment in China, seedling growth of the invasive South American weed, *Mikania micrantha*, was inhibited by the application of leaf litter extract from four native trees, *Schima superba*, *Castanopsis chinensis*, *Castanopsis fissa*, and *Cryptocarya chinensis*.

In order to determine the allelopathic strategy of trees, researchers must test extracts from their leaves, leaf litter, flowers and roots on weed seed germination and seedling growth, and monitor the response of weed seeds or seedlings to soil beneath the trees. CUMMINGS et al., (2012) reviewed published investigations of trees suspected of having allelopathic properties. Not all trees, however, demonstrate allelopathy. For example, FINE et al., (2006) found that fast-growing pioneer trees tend not to produce allelochemicals. This may be the result of a trade-off between energetic investment in rapid growth and chemical defense. This suggests that tree species traits may be correlated with allelopathic activity. If we knew which traits are most strongly predictive of allelopathy, we may be able to more rapidly identify allelopathic native tree species for weed control in forest restoration.

Incorporating plant residues and allelochemicals into the soil

In addition to identifying trees with allelopathic potential, research on allelopathy for forest restoration could include techniques for the use of plant residues or extracts at planting sites. Allelopathic plant residues can be surface-applied, as mulch, or incorporated into soil for weed suppression. Other potential weed-control agents include allelochemical extracts from plant parts, residues, leaf litter, or soil from around allelopathic plants. These too can be incorporated directly into soil or directly applied to target species. Although the allelopathic effects of weeds have most often been viewed as a hindrance to forest regeneration, it may be possible to exploit their allelopathic properties in order to aid it. For example, some invasive, highland, weed, species such as *Ageratina adenophora*, *Chromolaena odorata* and *Bidens pilosa* have allelopathic effects on seed germination and growth (Table 10.1). They may be useful sources of allelochemical extracts or soil incorporates to control other weed species.

Table 10.1 - Examples of invasive weed species and their allelopathic effects.

Weed species	Target species	Allelopathic effect	Allelo-chemicals	Citation
Ageratina adenophora (Spreng.) R.M. King & H. Rob.	*Arabidopsis thaliana*	Effect of root extract on germination of herb	Terpenes	ZHAO et al., 2009
Ageratina adenophora (Spreng.) R.M. King & H. Rob.	*Arabidopsis thaliana*	Effect of root extract on germination and growth of herb	Phenols	ZHOU et al., 2013
Bidens pilosa L.	*Raphanus sativus* *Echinochloa crus-galli* *Corticum rolfsii* *Fusarium solani* *Fusarium oxysporum*	Effect of leaf, stem, and root extracts on germination and growth of crops, weeds, and fungi	Phenols	DEBA et al., 2007
Centaurea diffusa Lam.	*Festuca ovina* *Koeleria laerssenii* *Agropyron cristatum*	Effect of root exudate on growth of native grasses	-	CALLAWAY & ASCHEHOUG, 2000
Chromolaena odorata (L.) R.M. King & H. Rob. & *Lantana camara* L.	*Capsicum frutescens* *Brassica chinensis* *Cucumis sativus* *Brassica juncea* *Amaranthus viridis*	Effect of leaf litter extract and soil, collected from invaded area on emergence and growth of crops and weeds	-	SAHID & JOHN, 1993
Rottboellia cochinchinensis (Lour.) Clayton	*Bidens pilosa* *Echinochloa crus-galli* *Lactuca sativa*	Effect of soil, collected from invaded area, on germination and growth	*Trans-p-* coumaric acid	MEKSAWAT & PORNPROM, 2010

Identifying sources of allelochemicals and synthesizing

The molecular composition and mode of action of some targeted allelochemicals may suggest novel strategies for herbicide action and thus spur the development of more effective herbicides (MACÍAS et al., 2007). Examples where this has been successful include the development of the commercial 'natural' herbicide product, NatureCur®, from black walnut (*Juglans nigra*) extract (SHRESTHA, 2009) and the commercial herbicide, glufosinate, based on the chemical structure of the natural product, bialaphos (MACÍAS et al., 2007). For a more complete review of prominent, known allelopathic compounds and their mechanisms of action, please see INDERJIT & DUKE (2003).

Advantages and limitations of allelopathy

The allelopathic potential of plants or their sensitivity to allelochemicals from other plants depends largely on the amount, concentration and form of the allelochemicals, as well as the timing of their introduction (ZIMDAHL, 2013). Allelochemicals may also have differential effects, depending on species. For example, HSU & KAO (2009) found that aqueous extracts of the leaves, stems, and roots of the introduced species, *Bidens pilosa*, inhibited germination and growth of the same species and a sympatric species, *B. bipinnata,* but not a second sympatric species, *Ageratum conyzoides*. This suggests that some allelochemicals have the potential to target specific weeds. Ideally, this could be used in forest restoration to target certain noxious weed species, while leaving desirable species, such as planted trees, unaffected. On the other hand, it may be difficult to predict the long-term effects of allelopathic interactions on non-target species, particularly when employing long-lived allelopathic trees in restoration plantings. Some trees, such as *Gmelina arborea* (Fig. 10.2) and *Eucalyptus*, are known to have such potent allelopathic properties that they decrease plant species diversity within their proximity (CHU et al., 2014).

When used directly as bioherbicides, allelochemicals may have significant advantages over traditional synthetic herbicides. These 'natural' herbicides may pose fewer environmental risks than synthetic herbicides do, if they target only certain species (NOLLET & RATHORE, 2015). Furthermore, rapidly decomposing allelochemicals reduce the risk of residual contamination and secondary transport from the planting site (DUKE et al., 2000). They may also decrease the incidence of herbicide-resistance in weed populations or provide alternative methods for control, where herbicide-resistance prevents use of conventional herbicides (ZIMDAHL, 2013). There are, however, some potentially significant limitations to using allelochemicals as herbicides and in herbicide development. The short environmental half-lives of many naturally-occurring allelochemicals may preclude their use as effective herbicides, since some phytotoxic persistence is often desirable in weed management. Moreover, obtaining sufficient quantities of extracts for effective weed control may be impractical (DUKE et al., 2000).

Given these limitations, it may be possible to use the molecular composition and mode of action of some targeted allelochemicals instead, to suggest novel strategies for herbicide action. This may spur the development of more effective herbicides that can be synthesized for application in forest restoration (MACÍAS et al., 2007; ZIMDAHL, 2013). However, the process of identifying, isolating, and determining the structure of the allelopathic compounds may be prohibitively expensive. Even after this process has been undertaken, it may be too costly or impractical to synthesize the complex phytotoxic molecules of naturally occurring allelochemicals in quantities sufficient for operational use (DUKE et al., 2000). Moreover, to comply with regulations, these potential products would still have to be tested for efficacy and toxicity.

AUTO-WEEDING FOR AUTOMATED FOREST RESTORATION

Auto-weeding refers to the automated application of herbicides to forest restoration sites for the purpose of weed control (Fig. 10.3). In order to apply allelopathy to auto-weeding, however, we must first identify the particular allelochemicals that target undesirable weed species and determine appropriate concentrations, application times, and application methods, as well as conduct a cost-benefit analysis. Furthermore, additional research is needed to determine whether the allelopathic effects are broad-spectrum or species-specific. We also need to identify biotic and abiotic interactions that may alter the production and effectiveness of the allelochemicals. For example, the concentration and production of allelochemicals by plants may be affected by nutrient deficiency (VARKITZI et al., 2010), stress (TONGMA et al., 2001) and soil microorganisms (BOREK et al., 1994). We should then characterize the conversion process and identify the degradation products of the allelochemicals in the environment (MACÍAS et al., 2007). Moreover, beyond lab or pot experiments, the development of practical application and formulation techniques are key to the effective use of allelopathic chemicals for forest restoration.

One potential use for auto-weeding is pre-emergent weed control on forest restoration sites (Fig. 10.3). These sites often possess a high diversity of weed seeds in the soil seed bank. These weeds may re-establish rapidly after land clearing and compete with planted or naturally regenerating trees. Application of allelochemicals could possibly be followed by a rest period, to allow biochemical processes such as chemical fractionation that may or may not require moisture to break down allelopathic compounds. Consequently, the timing of the initial application may be critical, because incorporation and degradation of the compounds may require interactions with seasonal abiotic processes, such as rain and biotic processes, such as soil microorganism activity (GIMSING & KIRKEGAARD, 2008). Aerial seeding would then follow, though reapplication of phytotoxic extracts may be need after seedling establishment, to control newly emerged weed seedlings.

INTEGRATED WEED MANAGEMENT FOR AUTOMATED FOREST RESTORATION

Allelopathy represents just one of several possible weed management strategies. Mechanical, cultural, and biological techniques also hold great promise for managing weeds in forest restoration. Rather than focusing solely on the development of biochemical tools, our goal should be to maximize the effectiveness of weed control, by combining allelopathy with other techniques into an integrated management system (NOLLET & RATHORE, 2015).

Allelopathy is a promising tool for future weed management strategies that may reduce the persistence of exotic weeds with fewer side-effects for people, property, and the environment. This contribution, however, is highly dependent upon the success of research into identifying and characterizing allelopathic species and chemicals, and the development of practical techniques for applying allelopathy to automated forest restoration.

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Figure 10.3 - Testing of auto-spraying for weed management in an agroforestry system

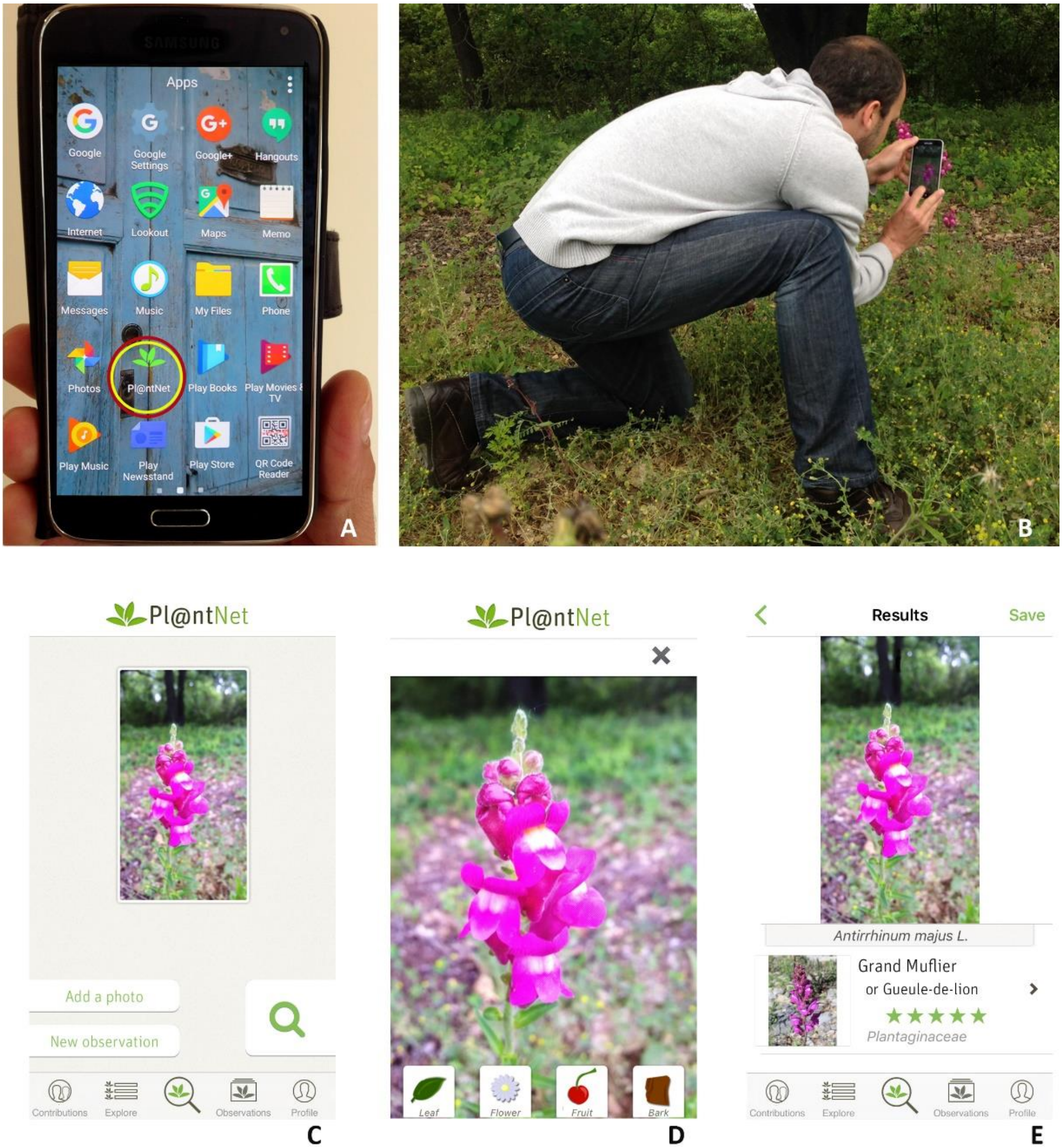

Figure 11.1. Using an automated plant identification application (Pl@ntNet). A, application displayed on a smartphone; B, plant of interest is photographed by user using smartphone; C, photo of plant as it appears in application; D, organ type depicted in photograph (flower) is manually chosen by user; E, identification results.

Chapter 11

BASICS OF AUTOMATED PLANT IDENTIFICATION

Pierre Bonnet[1] and Dawn Frame[2]

ABSTRACT

Historically, image-based dichotomous plant identification keys precede text-based ones by nearly one hundred years. Having lain in conceptual torpor for over 300 years, the notion of image-based identification has experienced a revival as a result of the development of modern applications which depend upon recent technological advances in electronic hardware (e.g., image sensors, network bandwidth, computer storage capacity) and software (especially image recognition systems and efficient large file browsing). There are essentially two different approaches to automated image-based recognition of plant species: Leafsnap and Pl@ntNet. A brief discussion of the two approaches is here presented. Regardless of the approach, for successful automated plant identification, there are several dataset requirements and these are laid out in the following paper.

Key words**:** Image-based identification, social network, crowd-sourcing, citizen science, multi-organ, computer vision, mobile application, botany.

INTRODUCTION

The wide disparity between the reality, both qualitatively and quantitatively, of the species making up Earth's biodiversity and our knowledge of it, has been called the "Taxonomic Gap" (DUBOIS, 2010). Until recently, species identification has been carried out by the use of dichotomous keys. Lamarck has long been credited with the invention of the dichotomous key to species, which he presented in his *Flore Français* (1778). However, new evidence suggest that the first dichotomous identification key was proposed by Richard Waller in 1689 (GRIFFING, 2011), and unlike Lamark's, which was text-based, Waller's was an image-based one, consisting of a series of water-colors of English herbs (GRIFFING, 2011). A great part of the problem of recognizing new species lies in knowing what has already been described. For the interested lay person, novice or confirmed taxonomist, text-based dichotomous keys have been the standard means of identifying species, and these

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are notoriously difficult to navigate even for professional taxonomists, and as such, they represent a major bottleneck to rapid species identification.

Early on, conceived as a labor-saving tool for the identification of common species cluttering up the taxonomist's workbench (GASTON & O'NEILL, 2004), automated species identification has come a long way in just over a decade. Hand in hand with technological improvements in hardware (e.g., image sensors, network bandwidth, computer storage capacity and memory) and software (especially image recognition systems and efficient browsing of large datasets), so too has the size and cost of equipment dramatically decreased leading to the democratization of computers and other portable devices such as telephones equipped with high-resolution cameras. Consequently, there has been an explosion of web-scale multimedia data and with it the emergence of innovative processing and applications (CHANG et al., 2012). Moreover, there has been a paradigm shift, such that now automated approaches to species identification are designed not just to recognize common species, but potentially any species (Fig. 11.1). Today, there are essentially two different approaches to automated image-based recognition of plant species as embodied by the following two systems: Leafsnap (KUMAR et al., 2012) and Pl@ntNet (JOLY et al., 2014a). Typically, automated identification systems, be it plant identification from images taken by hand-held cameras, aerial photography or even hyperspectral sensors, comprise two separate processes, which may be conducted sequentially or in parallel. The first process involves the analysis of known entities such as images of organs of known (properly identified) species. This data is used to generate a "training" set from which differences between species are "learnt", that is to say, discriminated; the second process involves the analysis of unknowns to be automatically identified (GASTON & O'NEILL, 2004).

BUILDING A DATABASE: WHAT TO WATCH FOR

Image-based, automated, plant-identification tools require large numbers of images, in order to provide several examples of the same visual concept (i.e., a species).

Kinds of examples to be included encompass both biological (e.g., intra-specific variation, different growth/developmental stages) and physical conditions (e.g., different lighting, taken from various angles).

Plant-image libraries typically suffer from one or more of the following problems, which often prevent their effective use as training data (JOLY et al., 2014a): -

1. Usually, few images per organ per species.
2. A few species having many images, but most having very few.
3. "Noise", i.e., cluttered or mixed images, errors in the metadata (tags, labels); illicit logging, coupled with weakness in monitoring.
4. High heterogeneity, in terms of acquisition protocols, views or tags.
5. High homogeneity — the result of few people taking images during a limited period of time in a restricted area, using an identical sensor and acquisition protocol.

The first problem is related to the fact that an image library is thought to be "good": [A] when it covers many species (so the interest is in obtaining high numbers of species, often with few photos each) or [B] when it covers only a few, usually common, species, represented by many images, whereas for the vast majority there are only a few images for illustrative purposes. From a machine-learning point of view, it is necessary to have many images of different organs, taken under different conditions.

Background noise (bullet point 3) can occur at the level of the image, affecting a machine's ability to rapidly discern the queried plant in the image, or at the metadata level, in terms of incorrect identification, organ name, view label and so on; i.e., noise here is equivalent to degree of metadata error.

Both high heterogeneity and homogeneity are sources of problems. High heterogeneity of photographing protocols (e.g., indoor, outdoor, studio, flat-bed scans) and variety of views (e.g., whole plants, portions thereof, landscapes or herbarium specimens) are problematic for image recognition and machine learning, as is heterogeneous metadata, such as the use of different terms for the same entity (e.g., leaf, leaves, foliage).

The final weakness, oddly enough, is too much homogeneity. Some datasets have been built especially for computer vision and machine learning and they contain categories having many different (well populated), numerically-balanced, homogeneous images without noise—the product of few specially trained people, who took photos over a short time period, in a restricted area, following a stringent acquisition protocol, using a single or few sensors. This leads to datasets, which lack diversity, greatly limiting their utility in the real world, but otherwise fulfilling most of the requirements of good datasets for computer vision and machine learning.

LEAFSNAP

Leafsnap was the first plant species mobile application (KUMAR et al., 2012) and is currently available for Apple mobile devices (iPod touch, iPhone and iPad). The dataset covers 185 tree species of the northeastern United States and Canada, and work is on-going to expand this to all tree species of the continental United States (http://leafsnap.com/about/). Recently, a United Kingdom version for iPhone has been developed called Leafsnap UK, which allows identification of 156 tree species (http://www.nhm.ac.uk/take-part/identify-nature/leafsnap-uk-app.html). Leafsnap is a visual recognition system designed for a single plant organ, the leaf. The requirements of this application are that the user must photograph on a solid light-colored background, a well-flattened leaf of the tree to be identified. The software then classifies the image (is it a leaf?), segments the image (separates background from leaf), extracts features (often involving compensation for curvature), compares resultant features with a labeled database, and then returns the species having the closest matches, totaling about five seconds for the whole process (KUMAR et al., 2012). Additionally, if the Global Positioning System (GPS) of the mobile device is turned on, the application allows a geographic information system (GIS)-based mapping of the study tree. The user can look through the returned results, which are associated with photos of other organs, views of the entire tree and a description, and make a final identification. Numerous specialists and trained volunteers took the photos forming the image database; it is composed of high-quality laboratory images of back- and front-lit pressed leaves (23,147) and a lesser number of field images (7,719) mostly taken outdoors on iPhones. It is important that the database be populated with many images because of the high degree of within species (infraspecific) variability in leaf shape and considerable variation in lighting conditions under which the query photos will be taken. Despite its most notable drawbacks of single-organ recognition, coverage of relatively few species and necessity to photograph under fairly stringent conditions, all a reflection of the relatively homogeneous training dataset, Leafsnap has been adopted by over a million users and pedagogic materials using it have been developed to teach adolescents botany in the United States.

PL@NTNET

Pl@ntnet represents an alternative approach to automated plant identification (Fig. 11.1). As mentioned above, homogeneity in training data severely limits wide applicability of an identification tool. In reaction to this, there has been a move towards collecting crowd-sourced data. This method must be judiciously applied else it can be burdened with too much noise (pt 3 above), e.g., if raw research results of ImageNet were simply filtered and consolidated by a crowd-sourced interactive application, wherein images were validated by only a few users (JOLY et al., 2014a). In an inverse manner to Leafsnap, Pl@ntnet is a multi-organ system that derives its training data from images taken using mobile devices operated by experts, amateurs and novices (crowd-sourcing). These campaigns were and are coordinated through a thematic social network, Tela Botanica, the largest French-language botany network in the world, having over 29 000 registered users living in more than 70 countries. For such a project to be successful, it had to be carefully organized from inception, and a series of work-flows were devised by a team of experts in botany, image recognition and software development.

The Pl@ntNet initiative focused on the development of innovative digital tools, specifically: (i) visual aids for taxonomic identification, (ii) collaborative revision of data quality and (iii) management of large volumes of botanical observations. In 2009, the project team created a small dataset of images of Southern European tree species leaves. This dataset was enriched soon after by complementary images of other organs of these same species in addition to other species (initially the most common tree and weed species), collected during campaigns organized by Tela Botanica and employing network members, in this way, novices, amateurs and experts collected images used for training a content-based identification tool. The forays were guided by experts, either in person or through an illustrated newsletter to members with, for example, seasonal suggestions of what species views to collect. In an interactive, collaborative manner through the website and application, end-users can propose and verify identifications and there exists a weighting system related to botanical expertise so that, for instance, an expert's identification is higher valued than that of a novice. Similar to other crowd-sourced media, photos of species are voted on for quality, often a motivating force for some participants. Identification is guided by experts by means of illustrated booklets and web-based links to references and other identification resources. The growing dataset produced mostly by amateurs is tested each year by ImageCLEF and LifeCLEF campaigns (JOLY et al., 2014b) using different algorithms for plant identification based on real-world data, that is, collected by non-specialists. The dataset allowed the testing and evaluation of plant identifications made not just from leaves, but also from flowers, bark, fruit. The process of continuous data integration by Pl@ntNet allowed the development of a growing computational platform able to manage and benefit from thousands of contributions (Fig. 11.2). This platform was first available on the web (2011) followed by an iPhone application in 2013 and Android in 2014. One of the major innovations of the Pl@ntNet platform has been the ability for the end-user to directly revise, in a collaborative manner, all visible data. Thanks to this continuous revision process, the application is able to cover an increasing number of species and has a growing number of images (Fig. 11.2). By creating a structured dataset, developing innovative tools for data browsing, and building a community of volunteers, the Pl@ntNet initiative made it possible to aggregate a huge volume of botanical observations (over 2 million observations are currently being analyzed) from the user community's identification requests. The created infrastructure has been used by more than a million and a half people, representing a wide range of users, from non-specialists to experienced botanical researchers, in over 150 countries in the world.

Table 1. Summary of the differences between Leafsnap and Pl@ntNet.

Characteristic	Leafsnap	Pl@ntNet
Organs	leaves	leaves, flowers, fruits, bark & habit
Setting	homogenous background	natural conditions
Criteria	mono-image, -criterion	multi-image, -criteria
Database type	static	dynamic (daily updates)
Image recognition	segmentation	content-based image retrieval using data mining
Contributors	few, trained specialists	many thousands of lay-photographers
Species number & Flora	185 North-eastern US, 156 United Kingdom	ca. 6000 mostly France
Plant growth form	trees only	any

PROOF OF CONCEPT

Pl@ntNet and Leafsnap are similar in that they are image-based identification systems available as free mobile applications, which can use relatively low-resolution images to provide a list of probable species in a few seconds. However, these two applications differ in many ways (Table 1) largely related to the acquisition of the training data. It is clear, whichever the system employed, that the future of automated plant identification lies in eschewing text-based dichotomous keys in favor of image-based applications. As Richard Waller in a letter to John Ray dated 5 April 1688 (DERHAM, 1718) aptly states when providing the rationale for his illustrated key "... my Design in these Tables being only to give an Idea of the Difference of Plants by *Pictures*, (the Representations of Beings) rather than by *Words* (the Representations of Pictures.) ...". Ray dismissed the idea and interestingly enough, his major opus *Historia Plantarum* (1686, 1688), which lacked illustrations, did not achieve the hoped-for success. Of course, designing watercolor illustrations is too time-consuming for rapid and efficient characterizations of numerous species, but with the vulgarization of inexpensive digital image sensors available in cameras and portable telephones, rapid and reliable plant identification is leaving the workbenches of the herbarium scientist passing through the hands of citizens-scientists and landing into the everyday life of ordinary people. We may never be able to completely bridge the taxonomic gap, but possibly with the aid of innovative identification tools in the hands of the many instead of the few, we will progress towards a better understanding of the natural world surrounding us.

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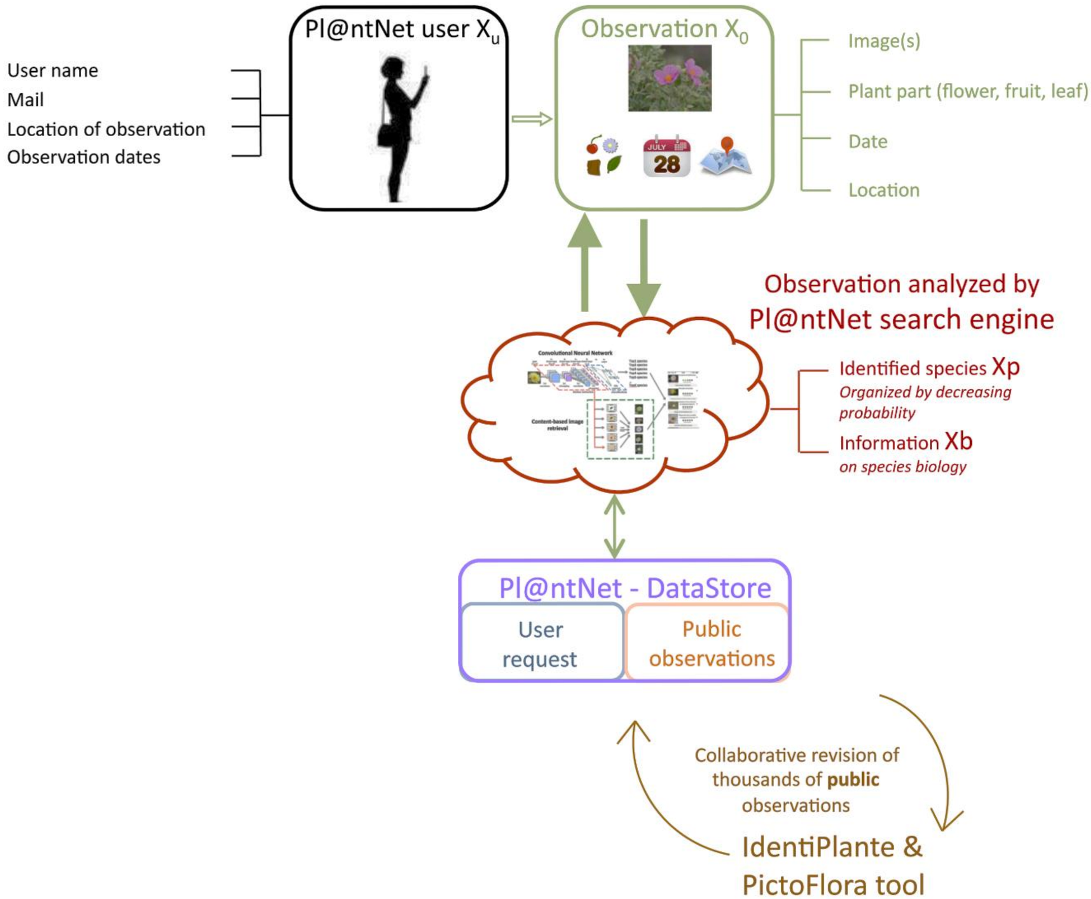
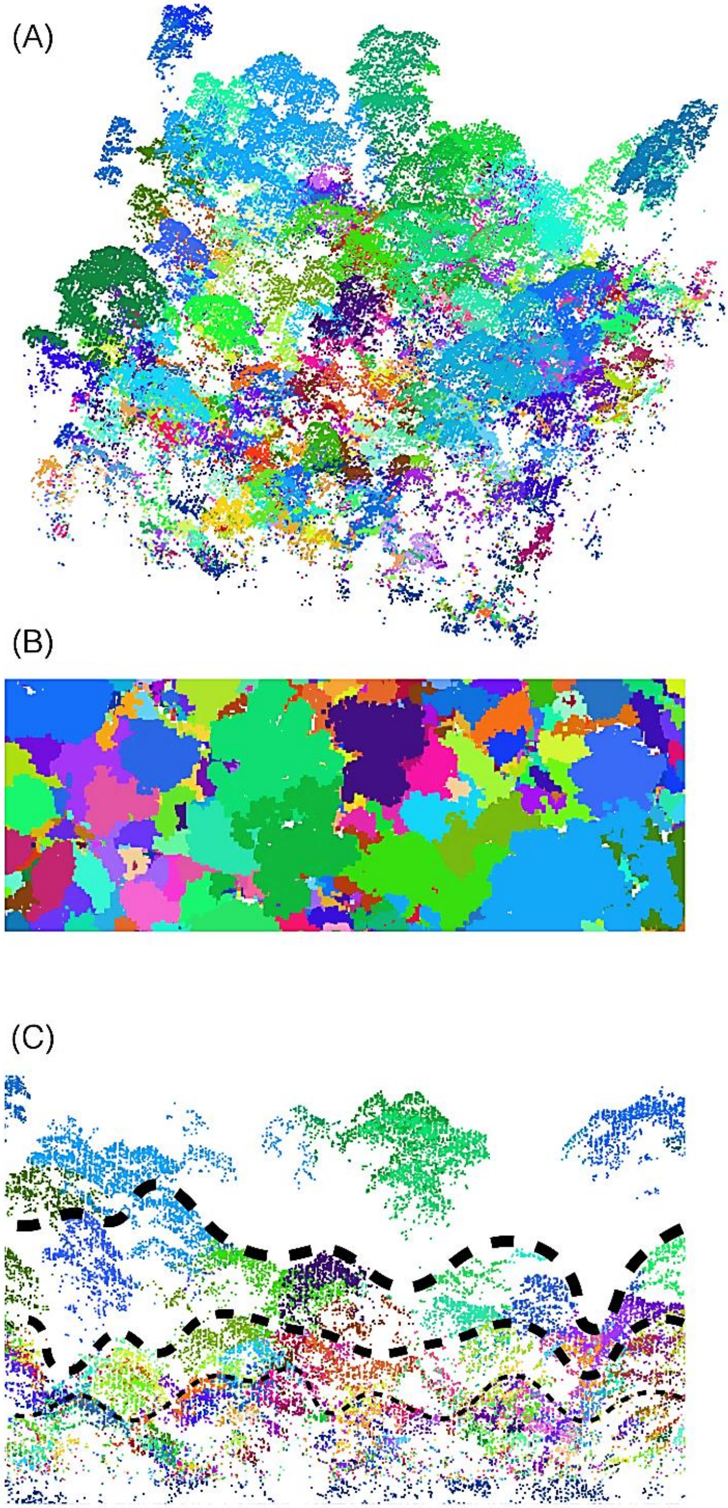


Figure 11.2. Outline of Pl@ntNet interactive workflow.

Figure 12.1



(A) A lidar point cloud from a manned aerial survey at Sepilok, Malaysia. Algorithmic (DBSCAN) segmentation was used to assign a different colour to each tree crown (oblique view).

(B) A horizontal projection of the canopy.

(C) A vertical cross-section of the canopy, with segmentation of canopy layers, shown

Chapter 12

AUTOMATED VEGETATION MONITORING FOR FOREST RESTORATION

Ryan Chisholm[1] and Tom Swinfield[2,3,4]

ABSTRACT

We discuss the potential of automating vegetation monitoring, to aid forest restoration. We propose that automated monitoring focuses on estimating forest biomass and tree diversity, because these are relevant to many ecosystem services, and they can be assessed with existing automated technologies, to some extent. We discuss the importance of setting baselines and realistic goals that take into account site history and landscape context. We review relevant technologies, including unmanned aerial vehicles (UAVs), lidar, multispectral and hyperspectral sensors, visible-light cameras and data-processing software. We discuss advantages and disadvantages of below- versus above-canopy surveys. We identify technological obstacles to automated monitoring, including the automation of tree-species identification in diverse forests, and the assessment of forest structure in high-density forests. These obstacles are particularly rele-vant to tropical forests, which are typically dense and diverse. We also identify battery lifetime as a limitation to large-scale surveys, and one that is unlikely to be alleviated soon. Despite these caveats, available technology is adequate for automating small-scale assessments of some forest variables that are relevant to restoration, particularly in less dense, less diverse temperate and boreal forests. A fruitful approach may be to use intensive ground-level and low-altitude automated surveys, to calibrate data from satellite imagery that is subsequently applied to monitor restoration over larger areas.

Key words**:** automated forest restoration monitoring, lidar, spectral imaging, unmanned aerial vehicle, automated species identification, battery

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SETTING THE GOALS OF AUTOMATED RESTORATION MONITORING

Forest restoration is an essential component of global efforts to protect biodiversity and mitigate climate change. Here we review automated techniques for forest restoration. Any discussion of effective forest restoration first requires the definition of explicit goals. If forest restoration equates to restoration of ecosystem services, then the question can be rephrased in terms of ecosystem services: which ones do we want to restore? Ecosystem services are categorised into regulating, supporting, provisioning and cultural functions (MEA, 2005). Regulating services include greenhouse gas regulation, nutrient cycling and hydrology. Supporting services include habitat provision and soil formation. Provisioning services are the provision of food, timber and other resources for human consumption. Cultural services include the provision of wilderness value and existence value to humans. In deciding which ecosystem services will be the subjects of automated monitoring, we must take into account: i) which ecosystem services are valued by stakeholders, ii) which can be feasibly measured with automated technology and iii) which may be proxies for other, harder-to-measure ecosystem services.

To answer the first question, we must consider the preferences of different stakeholder groups. Recreational forest users are likely to prize cultural services, such as wilderness value and a few key charismatic components of biodiversity. Biologists, on the other hand, will put more emphasis on regulating and supporting services and on cultural services that relate to biodiversity, defined more generally. Resource and environmental economists may emphasise provisioning services and perhaps economically quantifiable regulating services (e.g., carbon sequestration can be quantified with carbon credits) or cultural services (e.g., provision of wilderness value can be quantified as eco-tourism revenue).

In answer to the second question, only a few of these ecosystem services are likely to be measurable with automated technology in the next decade or two. For those related to forest biomass and physical structure, including habitat availability and microclimate (SCHWARTZ et al., 2000; ANDERSON & GASTON, 2013, JUCKER et al., 2018, DEERE et al., 2020), remote-sensing technologies exist that can be deployed for both above-canopy surveys (ASNER, 2007; MASCARO et al., 2011; ASNER et al., 2012; JAAKKOLA et al., 2017; KELLNER et al., 2019) and, to a more limited extent, for below-canopy surveys (FORSMAN & HALME 2005; MCDANIEL et al., 2012; CHISHOLM et al., 2013). For ecosystem services, related to tree diversity (e.g., existence value), incipient technologies can provide coarse estimates from lidar and hyperspectral imagery (DINULS et al., 2012; FÉRET & ASNER 2012; SCHWEIGER et al., 2018). For ecosystem services, related to specific tree species (e.g., provision of sustainable timber supplies), distinctive plants can be identified from remotely sensed imagery (ANDERSON & GASTON, 2013). However, many ecosystem services, such as hydrology and soil formation, do not relate directly to any of these measurable indicators. This is especially true for some of the more abstract cultural services, such as wilderness value. However, advances in artificial intelligence may prove fruitful even here.

Fortunately, and in answer to the third question, many ecosystem services, though difficult to measure directly by automated means, are indirectly related to tree biomass and diversity. A forest is defined by the presence of trees taller than 5 m, with canopy cover of greater than 10% over an area of at least 0.5 ha (FAO, 2010). Consequently, focussing on forest biomass, as a primary indicator of restoration success, makes sense. Forests that have high values of standing biomass contain large carbon stocks (ZAKI & LATIF, 2017) and thereby contribute to global climate regulation; though young forests sequester new carbon faster than old-growth forests do (POORTER et al., 2016). High-biomass forests also provide humans with timber, non-timber forest products and recreational value. The biodiversity of other taxa, including insects and birds, is correlated with plant diversity and the presence of certain habitat structures, such as large trees (ZHANG ET AL., 2016, DEERE et al., 2020). This all suggests that tree biomass and diversity are good proxies for general biodiversity and associated ecosystem services. Thus, in this review, we focus on tree biomass and tree diversity, as key indicators of forest condition. They are relatively straightforward to measure and, directly or indirectly, indicative of many key ecosystem services.

The remainder of this chapter is structured as follows. In the section "Metrics of Forest Restoration", we discuss how our two indicators — tree biomass and tree diversity — can be measured, both directly and indirectly. In the section "Technologies for Forest Restoration Monitoring", we discuss technical aspects of technologies that can potentially automate these measurements. In the section "Above- vs Below-Canopy Monitoring", we discuss above-canopy and below-canopy approaches to automated monitoring of forest restoration. Finally, in the section "Summary and Conclusions", we propose a roadmap for future development of automated forest restoration monitoring.

METRICS OF FOREST RESTORATION

Measuring forest recovery is meaningful only insofar as appropriate targets for indicator variables can be set. It is crucial that restoration baselines and targets are set in context (ASHTON et al., 2001; LAMB et al., 2005). For example, targets ought to consider the initial biomass and diversity when restoration started, as well as local constraints on biomass accumulation and diversity for the site. If baseline data for the target site are not available, efforts should be made to find appropriate baseline sites that match the target site's abiotic conditions (HUETTNER et al., 2009; PÉREZ-CRUZADO 2014). Distance to intact forest should also inform expectations of forest recovery rates. With these guidelines in mind, we now discuss the metrics of tree biomass and diversity that are potentially viable for automated monitoring.

For estimating tree biomass, the most direct non-destructive method is first to calculate the volume of standing trees and then apply per-tree wood density values. Indirect methods involve measuring variables, such as top-of-canopy height, that are correlated with tree biomass (CLARK et al., 2011, SWINFIELD et al., 2019). Such indirect methods come with caveats: they must be calibrated, using field data and can be biased if calibrated using data from sites having different characteristics from the focal site (e.g., methods calibrated at dry sites will be unlikely to give accurate results at wet sites). Monitoring canopy height can also be used to detect ongoing disturbances, such as natural tree falls and illegal logging (MILLER et al., 2000).

For estimating tree diversity, direct metrics include species richness and Shannon diversity, but these may be impractical to measure, necessitating the use of surrogates. One approach is to measure the spectral diversity of the forest canopy. Spectral diversity is defined as the variation in reflectance spectra usually measured per unit area. Other options include summarising spectra to hypervolumes that describe multidimensional variation (SCHNEIDER et al., 2017), or by using an approach that counts the number of distinct spectral clusters (BONGALOV et al., 2019). Diversity is also assumed to increase with successional stage, especially in early stages (CHAZDON 2008a). However, measuring successional stage can be complicated, because multiple forest successional pathways are possible from the same initial condition (WALKER et al., 2007; CHAZDON, 2008b). The rate and pathway of recovery is governed by (1) the extent of degradation before restoration, (2) the degree of ongoing disturbance and (3) the influx rate of late-successional propagules (ASHTON et al., 2001; LAMB et al., 2005). Successional stage can be tracked using automated technology, by assessing the abundance of distinctive early-successional species, canopy cover and canopy height (D'AOUST et al., 2004; KALACSKA et al., 2007). Canopy cover may be a useful metric in the very early stages of restoration, but in tropical forests the canopy closes relatively quickly, when pioneers still dominate and the forest is far from its climax condition (KABAKOFF & CHAZDON, 1996; MONTGOMERY & CHAZDON, 2001). Thus, the abundance of certain species could serve as an indication that succession, towards a high-biomass, high-diversity state, is being retarded.

Tree physiology metrics may also be useful for monitoring the progress of forest restoration. These metrics include photosynthetic activity, nitrogen concentration, water stress and leaf area index (LAI). Context is again critical. High water stress, for example, may be a warning signal of restoration failure in a wet forest, but not in a seasonal forest. SALAMÍ et al. (2014) reviewed metrics, including normalized difference vegetation index (NDVI), greenness index, green normalized difference vegetation index and photochemical reflectance index. NDVI, in particular, is widely used to classify different land-cover types, for which it is broadly effective. However, it has similar limitations to canopy closure metrics, because NDVI saturates at fairly low values of LAI (WANG et al., 2005).

TECHNOLOGIES FOR FOREST RESTORATION MONITORING

We now turn to technologies that can be used to collect and analyse data for the purposes of estimating the metrics, discussed above. We focus on technologies for ground-level or low-altitude deployment, which can be feasibly implemented by practitioners at reasonable cost. Potential technologies for monitoring forest restoration can be divided into i) the platform and ii) the sensors mounted on the platform. An illustration of the kids of technologies we consider is shown in Fig. 12.2. These technologies, for forest monitoring, are also reviewed in GUIMARÃES et al. (2020), although without specific reference to restoration. We recognise that satellite imagery represents a valuable source of information for forest monitoring, but do not review this, because it is a large and well-developed topic in its own right, and in any case, satellite imagery must be calibrated with data from near-ground technologies (KELLNER et al., 2019).

Platforms

Potential platforms for forest restoration monitoring are (i) stationary platforms, (ii) mobile ground-based vehicles and (iii) unmanned aerial vehicles (UAVs). The most straightforward are stationary platforms. They can carry heavy payloads, but data are collected only from a single location. Ground-based vehicles overcome this limitation, but are restricted to relatively flat, solid paths, free of debris, often in heavily managed forests. The most feasible platforms, for automated assessment of forest quality over large scales, are UAVs.

For forest monitoring, two main kinds of UAV are suitable: (i) rotorcraft and (ii) fixed-wing aeroplanes (KOH & WICH, 2012; DANDOIS & ELLIS, 2013; LISEIN et al., 2013; ZARCO-TEJADA et al., 2014; GUIMARÃES et al., 2020). COLOMINA & MOLINA (2014) provide a useful overview of UAV systems, including sensors and software, for remote sensing. Both open-source and commercial software are available for guidance and ground monitoring (e.g., Mission Planner). This software is rapidly evolving and includes functions for navigation in three dimensions, automatic transect grids and the ability to trigger certain actions at specified times or locations.

Remote-piloted UAVs are widely available, but for truly automated monitoring, UAVs should be autonomous. Navigation software work well above the forest canopy, but software for autonomous, below-canopy surveys is still largely in development. Note that, at the time of writing, legislation governing UAVs is highly variable among countries and still in flux. The definition of UAV varies by country and usually applies above some weight threshold. Many countries require a permit to fly a UAV and UAVs are typically prohibited from flying above a certain height. Forest restoration practitioners should be aware of local legislation in order to understand the restrictions these impose on automated monitoring (see Chapter 14).

Sensors

Sensors, useful for forest restoration monitoring, include those that measure light from different parts of the electromagnetic spectrum, and those that measure sound. In the case of light sensors, wavelengths reflected or absorbed by the land surface, are detected as pixels of information. Sensors, useful for forest surveys, are lidar, visible-light cameras, multi- and hyper-spectral sensors. For forest monitoring with conventional cameras, off-the-shelf models (still and video digital cameras) are adequate for photogrammetry, including two- and three-dimensional spatial reconstructions (see p 176) (DANDOIS & ELLIS, 2010; ROSNELL & HONKAVAARA, 2012).

Lidar sensors are heavier than conventional cameras (1 kg or more) and more expensive, but they collect more precise structural information. While cameras record a passive signal of the incident light image falling on the sensor, lidar devices transmit a laser signal and record the time taken for light, reflected from surfaces, to return to the sensor. Since laser light penetrates thin or incompletely solid surfaces, such as canopy leaf layers, reflection may occur at multiple depths from the uppermost canopy to the ground surface. The ability of the sensor to record these multiple returns, allows lidar to reconstruct multilayer structures. This is driving its rapid adoption in forest monitoring (LIN et al., 2011; HEIKKI, 2013; TSUBOUCHI et al., 2014; CUSHMAN & KELLNER, 2019; JONES et al. 2020). At present, lidar is prohibitively expensive for many purposes, particularly compared with the low costs of basic UAVs. However, the demand for diverse lidar applications is driving the development of lighter and cheaper lidar devices, which will make their use for forest restoration monitoring more cost-effective (WALLACE et al., 2012).

Multi- and hyper-spectral sensors collect data over a broad range of wavelengths of the electromagnetic spectrum. While conventional cameras have sensors in three visible-light bands (red, green and blue), multispectral cameras have sensors that cover a greater diversity of wavelengths, from the infrared and visible regions. Hyperspectral sensors are able to measure reflected light across the electro-magnetic spectrum, often from ultraviolet to short-wavelength infrared (400–2500 nm) within 200 or more consecutive bands (ADÃO et al., 2017). Because forest vegetation reflects light beyond the visible range, the additional information, provided by multi- and hyperspectral sensors, is of high value for vegetation monitoring, particularly for detecting plant species and measuring functional traits e.g., stress responses and leaf mass per unit area (ZARCO-TEJADA et al., 2013, ASNER et al., 2015, SCHNEIDER et al., 2017, SCHWEIGER et al., 2018).

Localisation technologies

Sensor information from forest surveys, is most useful if location data are available. Such data can be used to construct maps of the environment or to add information to existing maps. The ideal localisation techno-logy is GPS, but it is not available everywhere (e.g., steep valleys or below the canopy (see page 180)). Alternative technologies include ultrasound (FUKUJU et al., 2003; MEDINA et al., 2013) and ultra-wideband radios (GEZICI et al., 2005). These operate over short distances, and communicate their position using ground-based sensors of known position. Unfortunately, the set-up costs of such systems can be high. Another option is Simultaneous Localisation & Mapping (SLAM) (BACHRACH et al., 2011; DURRANT-WHYTE & BAILEY, 2006a; DURRANT-WHYTE & BAILEY, 2006b; RYDING et al., 2015; LI et al. 2016, ZAFFAR et al., 2018). With SLAM, inputs from platform-borne sensors, including lidar and visible-range cameras, are processed in real time, to create a map of the environment that is used for platform navigation. Advances in forest-based SLAM are anticipated, driven by demand for military and commercial applications. However, the geographical range of UAVs using SLAM is limited by the precision of the SLAM software, which decreases with distance, due to error accumulation. Despite their limitations, these alternative localisation technologies may serve as stepping-stones towards improved GPS, or may be used in conjunction with GPS.

Data processing: forest physical structure and tree biomass

Much of the data collected from autonomous vehicles that monitor forests can be processed offline. Data may be collected manually by operators, but preferably the vehicle would continually transmit data to a base station for intensive post-processing, and only store enough data on board to navigate within its environment (e.g., via SLAM). We now discuss offline processing tools, for assessing forest structure from visual imagery and lidar.

Photogrammetry and stereo-photogrammetry, from aerial photographs of forests, have long been applied to estimate stand size, canopy depths and stand volumes. The challenge for fully automated monitoring is to design algorithms that match or exceed the performance of humans in measuring these forest properties. For example, canopy openness can be automatically measured from aerial imagery, by applying thresholding algorithms that classify pixels as either canopy or gap, according to light intensity values, usually from a single light band. A basic version of the technique is straightforward to implement, but efforts should be made to exclude obliquely captured images and apply lens-specific, optical corrections, to ensure that measurements are standardised by area (JENNINGS, 1999). However, this approach has now been made largely redundant by more advanced photo-grammetric approaches (see below).

Techniques for estimating forest physical structure from remotely sensed data rely on software that can create and analyse point clouds derived from visual imagery or lidar. In the case of lidar, techniques developed for manned aerial surveys (LISEIN et al., 2013) are mostly transferrable to UAV surveys (e.g., LIN et al. 2011; WALLACE et al., 2012; HEIKKI, 2013; ZAHAWI et al., 2015; SWINFIELD et al., 2019). In the case of visual imagery, point clouds are constructed by Structure-from-Motion (SfM) (WESTOBY et al., 2012; IGLHAUT et al. 2019), an advanced photogrammetry technique that reconstructs three-dimensional surfaces by identifying common features across multiple two-dimensional images (LISEIN et al., 2013; COLOMINA & MOLINA, 2014). Deployment of SfM in forests is possible from point clouds scanned either above (WESTOBY et al., 2012; ZAHAWI et al., 2015) or below the canopy (FITZGIBBON & ZISSERMAN, 1998; POLLEFEYS et al., 2004; ROSNELL & HONKAVAARA, 2012; PIERMATTEI et al., 2019). It does not require camera positions to be known, although this greatly aids the process and enables point clouds to be located in absolute space. Both proprietary (e.g., Agisoft Photoscan, EnsoMOSAIC, PIX4Dmapper) and open-source (e.g., EcoSynth, MICMAC, Visual SfM and Open Drone Map) software is available for implementing SfM (GUIMARÃES et al. 2020). The point clouds, derived from SfM, have the advantage that densities are orders of magnitude greater than those from airborne lidar, although terrestrial laser scanning and drone-mounted lidar also produce very high point densities. Analysis of dense point clouds is computationally intensive and therefore, high performance computer services, including clusters of graphical processing units and cloud-computing services, improve its feasibility (LAVY et al., 2015).

Point clouds from lidar or SfM can be processed to measure the height and structural properties of forest canopies as well as the size of individual trees (WULDER et al., 2012). An example of SfM is shown in Fig. 12.3. Canopy height is computed as the difference between the canopy and terrain surfaces. The surfaces are constructed using algorithms parameterised for site-specific topographic and forest conditions. Digital terrain models are estimated by applying statistical smoothing algorithms to classified ground points. Consequently, their accuracy is a function of the density of true ground returns and topographic variation. Point clouds from SfM can produce accurate digital terrain models, when canopies are open or discontinuous (ZAHAWI et al.; 2015, SWINFIELD et al., 2019). When canopies are closed, canopy height can be underestimated, but often to a predictable degree and can therefore be corrected. Point clouds from lidar can produce accurate digital terrain models, even for high-biomass forests on uneven terrain (PATENAUDE et al., 2004; WALLACE et al., 2012; ASNER & MASCARO, 2014; VAGLIO LAURIN et al., 2014). An example lidar point cloud is shown in Fig. 12.1. Comparison of point clouds from different time points can yield information about tree growth, as well as ongoing disturbances such as natural tree falls and illegal logging (MILLER et el., 2000).

Point cloud data can also be processed, to estimate individual tree parameters, such as height, stem diameter, crown diameter and volume (DALPONTE et al., 2011; WILLIAMS et al., 2019). Tree heights are detected as local maxima within the canopy height surface, by scaling the detection window according to tree size. Crowns can also be segmented, using algorithms that search for tree edges, based upon changes in height or spectral signals between adjacent points (HYYPPA et al., 2001; ERIKSON & OLOFSSON, 2005; HOLMGREN & LINDBERG, 2014; WALLACE et al., 2014; TOCHON et al., 2015). Several algorithms exist to implement crown segmentation; one example is shown in Fig. 12.1. The addition of spectral information can aid in segmentation but misalignment in space and contrasting spatial resolutions introduces an additional layer of complexity. Accurate measurement of particularly heterogeneous canopies may require forest-specific allometric relationships between crown diameter and tree height, to prevent unrealistically sized crowns from being delineated. Tree volume can be estimated using algorithms for individual stem segmentation (e.g., KELLNER et al. 2019).

Once data on individual tree parameters have been computed, they can be used to track tree growth rates or calculate stand-level parameters, such as stem-size distributions, biomass and carbon (PATENAUDE et al., 2004; ASNER & MASCARO, 2014; VAGLIO LAURIN et al., 2014). Estimates of the dimensions of the tallest or dominant sized trees can be used to infer site quality and thus the maximum potential biomass that can be attained at any given site, assuming that maximum stocking capacity is achievable where edaphic and climatic conditions are optimal. Estimating the properties of the sub-canopy is more difficult due to obscuration by the overlying canopy, but even here lidar is able to reconstruct vegetation density as the ratio of reflected to incident lidar energy. This technique is the basis of the Global Ecosystem Dynamics Investigation (GEDI) on board the International Space Station (DUBAYAH et al., 2014) and has been implemented successfully using discrete airborne lidar also (ARNQVIST et al., 2020).

Estimating forest biomass and structure, using the techniques described here, is most feasible in forests that have relatively low vegetation density or are deciduous, facilitating the scanning of comprehensive point clouds from above-canopy UAVs. Such forests include most temperate and boreal forests. For dense evergreen tropical forests, other approaches, including below-canopy UAVs, may ultimately be needed (see page 180).

Data processing: tree diversity

Monitoring tree diversity recovery at a restoration site, following implementation of management interventions, can be challenging. A robust tool for identifying tree species automatically would be the holy grail of tropical forest ecology and would enable spatial assessments of species distributions on unprecedented scales. In forest restoration projects, it would facilitate accurate estimates of both tree diversity and tree biomass — the latter via application of species-specific wood density values. However, at present, even the best statistical models, and indeed expert humans, can identify only a handful of tree species from remotely sensed imagery (MARTIN et al., 1998; PU, 2009; ERINS et al., 2011; GARZON-LOPEZ et al., 2013; BALDECK et al., 2015; WANG et al. 2019; NATESAN et al., 2020; SOTHE et al., 2019). These statistical approaches will continue to improve, and may become adequate for species-poor forests, but for species-rich tropical forests it is possible that we will never be able to distinguish the hundreds or thousands tree species that coexist in them from imagery alone.

One general approach to tree species identification is to classify pixels into species, based on their spectral properties. This can work for forests with relative few tree species, but the complexity of the classification problem increases rapidly with tree diversity. The essential problem is that the number of photo-reactive molecules and architectural arrangements, found in vegetative tissue, is limited and intraspecific phenotypic variation in spectral properties (driven by genotypic variation and environmental heterogeneity) is not necessarily low relative to interspecific variation. One option is identification based on spectral classification from conspicuous flowers, but this depends on surveys being frequent enough to capture potentially narrow flowering periods. Another approach is to classify species based on their geometry, derived from imagery points clouds. This includes the sizes of features such as leaves and branches, and repeating patterns, which can be measured using structural or textural metrics. Successful applications to date have involved only small numbers of species in temperate forests (e.g., KUMAR et al. 2012; OTHMANI et al. 2014; TORRESAN et al. 2017; SOTHE et al., 2020; KRŮČEK et al. 2020).

If species-level identification of trees proves infeasible in species-rich forests, an alternative would be to separate species into broad groups, such as functional groups. For example, disturbance-responsive species, such as pioneer trees, can have especially large leaves and open crowns, and concentrations of chemicals that support high rates of photosynthesis (NOGUEIRA et al., 2004). Another alternative is to measure the overall spectral or textural signature or diversity of a forest and to map this to estimate species diversity using pre-established relationships (DALPONTE et al., 2008; FRICKER et al., 2015). Such approaches may be sufficient during the early stages of succession, when diversity is relatively low, but perhaps not during the later stages of succession, when finer gradations of diversity become important for assessing restoration progress.

More sophisticated methods of tree species identification could improve biomass estimation at forest restoration sites as well, by allowing species-specific wood density estimates to be used in calculations. In the long term, it may be feasible to identify trees from DNA samples taken from the stem itself. At first, this would require UAVs to collect field samples and return them to the lab; later, *in situ* identification may be possible. The latter may sound implausible, but the cost of sequencing has fallen by over five orders of magnitude since the turn of the century and the size of sequencing equipment has shrunk concurrently. It will take substantial human resources upfront to create the DNA markers for thousands of forest species, but in some cases this work is already being done (KRESS et al., 2009; LAHAYE et al., 2008; STEELE & PIRES, 2011; KRESS 2017).

Batteries

Over the next few decades, the main factor, limiting development of autonomous forest monitoring, will be battery technology (GUIMARÃES et al. 2020), particularly below the canopy, where energy is constantly required to manoeuvre UAVs in three dimensions. In recent decades, progress in many technologies, relevant to automated forest monitoring, has been rapid e.g., micro-processor speed and DNA sequencing, but battery technology has lagged (SCHLACHTER, 2013). Whereas the transistor count on microprocessors has doubled roughly every two years, the doubling time of battery energy density has been 10 years or more. Indeed, battery technology is the current limiting factor in the development of many technologies, from vehicles to smart phones. The limitations of UAV batteries also prohibit the use of the most powerful sensors, because they are heavy and energy-demanding.

We predict that within a decade or two, most of the technical challenges of automated forest monitoring will be solved, but the range of vehicles and therefore the scope of monitoring efforts will still be limited by batteries. In the longer term, revolutionary battery technologies may emerge that will alleviate these limitations. In the meantime, innovative solutions may expand the potential scale of below-canopy surveys. For example, UAVs with the ability to float or perch would improve energy efficiency, while solar-powered charging stations could greatly extend operating times in the field. Alternative fuels, such as hydrogen fuel cells, have recently been developed for UAVs and should also be considered.

ABOVE- vs BELOW-CANOPY MONITORING

Above-canopy surveys are by far the most widespread and feasible strategy for forest restoration monitoring at present. They can be carried out with low risk of collision with trees or other objects, which means they can follow preset trajectories or waypoints and can be conducted by either fixed-wing UAVs or rotorcraft. Because fixed-wing UAVs have longer battery lives than rotorcraft, a single above-canopy flight can last from hours to almost indefinitely, as advances in solar powered flight have demonstrated (SACHS et al., 2009). Furthermore, can easily connect to Wi-Fi, telecommunications, and GPS networks. Many studies have reported successful flights of UAVs above the forest canopy or through cleared areas within forests (DANDOIS & ELLIS, 2010; LIN et al., 2011; WALLACE et al., 2012; ANDERSON & GASTON, 2013; ZAHAWI et al., 2015; JAAKKOLA et al. 2017; KELLNER et al. 2019), many using autonomous navigation.

Below-canopy monitoring is a useful complement to above-canopy monitoring. It can reveal a wealth of information about a forest's internal structure, including the distribution of stems and their biomass. Indeed, data from below-canopy surveys of some kind (whether automated or not) can be necessary to calibrate above-canopy methods for estimating forest biomass and structure. Below-canopy monitoring also opens up new possibilities for automated tree identification, based on bark or DNA samples. To date, most applications of automated below-canopy forest sensing have used stationary platforms (Watt & Donoghue, 2005; Forsman & Halme, 2005; McDaniel et al., 2012; Heikki, 2013; Tsubouchi et al., 2014). Other applications have involved humans carrying a sensor around inside forests (Ryding et al., 2015). Such methods do not constitute automated forest monitoring, but at least demonstrate the potential usefulness of mobile, below-canopy sensors. Several studies have used ground-based vehicles (usually remote-piloted, but sometimes autonomous), carry-ing sensors in forests (Miettinen et al., 2007; Rasmussen et al., 2013), but the application of these is likely to be limited to sparse, young forests or well-maintained plantations: most natural or semi-natural forests present too many obstacles (fallen logs, stumps, etc.) to ground-based vehicles.

The best long-term prospects for automated, large-scale, below-canopy, forest monitoring lie in rotorcraft, although flying rotorcraft autonomously through a forest understorey is fraught with technical difficulties. Navigation and collision detection are challenging tasks, compounded by unreliable GPS signals, due to interference or attenuation of the signal by the forest canopy. Rotorcraft and the advanced sensors required for navigation are energy intensive, which severely limits battery life. Nevertheless, some progress has already been made with relatively simple tasks, such as estimating tree diameters in a stand of planted trees (Chisholm et al., 2013).

SUMMARY AND CONCLUSIONS

We see a bright future for automated forest restoration monitoring, driven by exciting new and imminent technological developments in both software and hardware. However, for this technology to be effective, careful thought must first be given to fundamental practical considerations about how progress towards restoration is best assessed. We have proposed that restoration monitoring should focus on indicators that are relatively straightforward to measure and that reflect a broad array of ecosystem services. We have proposed tree biomass and tree diversity as two such broad indicators. Furthermore, we have emphasised the importance of defining baselines and of setting targets for restoration that are appropriate for the landscape context, i.e., that match, as closely as possible, the attributes of the original forest at the same location and that consider what is realistically attainable, given the current landscape matrix.

The technologies, on which automated forest restoration monitoring relies, fall into three broad categories: UAVs, sensors, and data-analysis software. Of these, UAVs, in particular, are an enabling technology for automated forest restoration: they permit cost-effective tracking of recovery processes over large spatial scales and at fine temporal resolutions. Surveys, based on UAVs, have further advantages in that they can be implemented rapidly in response to demand (e.g., a mast fruiting event) and data can be processed in near real time to direct management actions. Automated surveys are also likely to be more reliable than human-based ones. While they are not error-free, the errors that do occur are likely to be more consistent than errors in human-collected data and therefore easier to control.

Restoration practitioners can already draw inspiration from several recent studies that describe successful above-canopy forest surveys with autonomous fixed-wing drones. However, comprehensive restoration monitoring, at least in high-density tropical forests, requires not only above-canopy surveys but also below-canopy surveys, which are much more challenging (Fig. 12.2). To date, below-canopy surveys have been focussed on very specific tasks, such as high-resolution, three dimensional, lidar scanning of small areas. Future advancements, including the use of SLAM to enable autonomous movement through vegetation, will expand the areas accessible to below-canopy UAVs.

Another major outstanding challenge for forest restoration monitoring is automated tree species identification. With potentially thousands of tropical tree species in a single square kilometre of forest (PLOTKIN et al., 2000), it seems unlikely that algorithms that rely on coarse structural or spectral characteristics, derived from image data, will ever consistently classify the majority of species. A better option, in the long term, may be for UAVs to collect genetic material for DNA barcode analysis — advances in genetic sequencing and barcoding are currently revolutionising species identification (KRESS et al., 2009; ZHANG et al., 2016; KRESS 2017).

Perhaps the biggest long-term limitation of above-canopy and especially below-canopy forest restoration monitoring is battery technology. This limitation is unlikely to be overcome soon, since, historically, the rate of improvement of battery efficiency has been slower than that of other technologies.

We emphasise that this review has been intentionally broad-ranging and has given only an overview of each relevant technology. We direct anyone, intending to carry out automated forest monitoring, to further reading in our reference list, in particular recent reviews on topics including UAVs (TORRESAN et al. 2017; GUIMARÃES et al. 2020), SLAM (LI et al. 2016), SfM (IGLHAUT et al. 2019), DNA barcoding (KRESS 2017) and automated tree identification (WANG et al. 2019).

We foresee a near future, in which forest restoration monitoring relies on a combination of coarse, large-scale, above-canopy surveys and detailed, smaller-scale, below-canopy surveys (Fig. 12.2). The former will include analyses of satellite imagery, which is becoming increasingly available at high-resolutions and large scales, heralding a "golden age" in remote sensing (KELLNER et al., 2019). Initially, humans will continue to be heavily involved in some aspects of monitoring. However, the rising costs of manpower, falling costs of technology and its rising quality will all catalyse the move towards automation. In recent years, rapid development of both UAVs and sensors has been driven by military, engineering and commercial applications. These drivers should continue to deliver technological windfalls for forest restoration in the years to come.

Future priorities for research include: -

1. broader implementation of existing technologies, to assess which of them are already effective and identify those in need of improvements;
2. further development of tools for automated tree species detection and recognition;
3. reliable techniques for co-registration of geolocated data, to improve the precision of multi-temporal assessments;
4. a solution to below-canopy, autonomous, navigation problems;
5. creative workarounds to battery-life limitations, while we await the development of next-generation battery technology and
6. effective calibration of metrics from satellite imagery with data from ground-level and low-altitude surveys.

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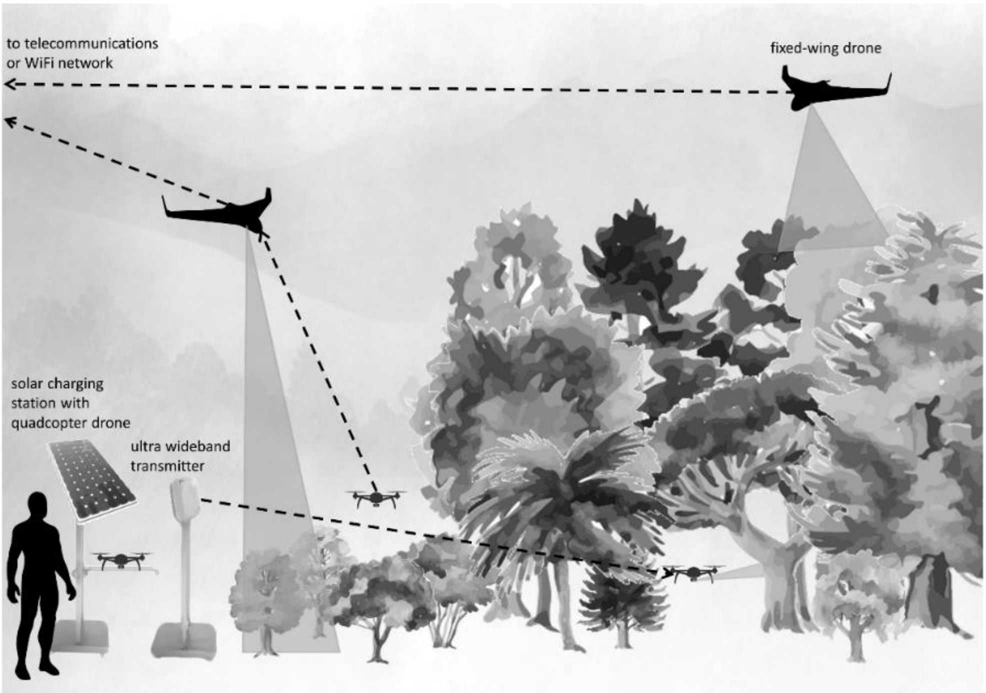

Figure 12.2 – Automated Forest monitoring is likely to comprise a mixture of above- and below-canopy technologies, working together, to measure and track forests during the restoration process. This schematic demonstrates how one such integrated system may be designed, with fixed-wing unmanned aerial vehicles (UAVs) collecting data at the landscape scale, supplemented by more precise measurements from rotorcraft or ground-based UAVs, working at lower altitudes and below the canopy. Data are transmitted back to researchers either directly or indirectly via other drones and telecommunications networks.

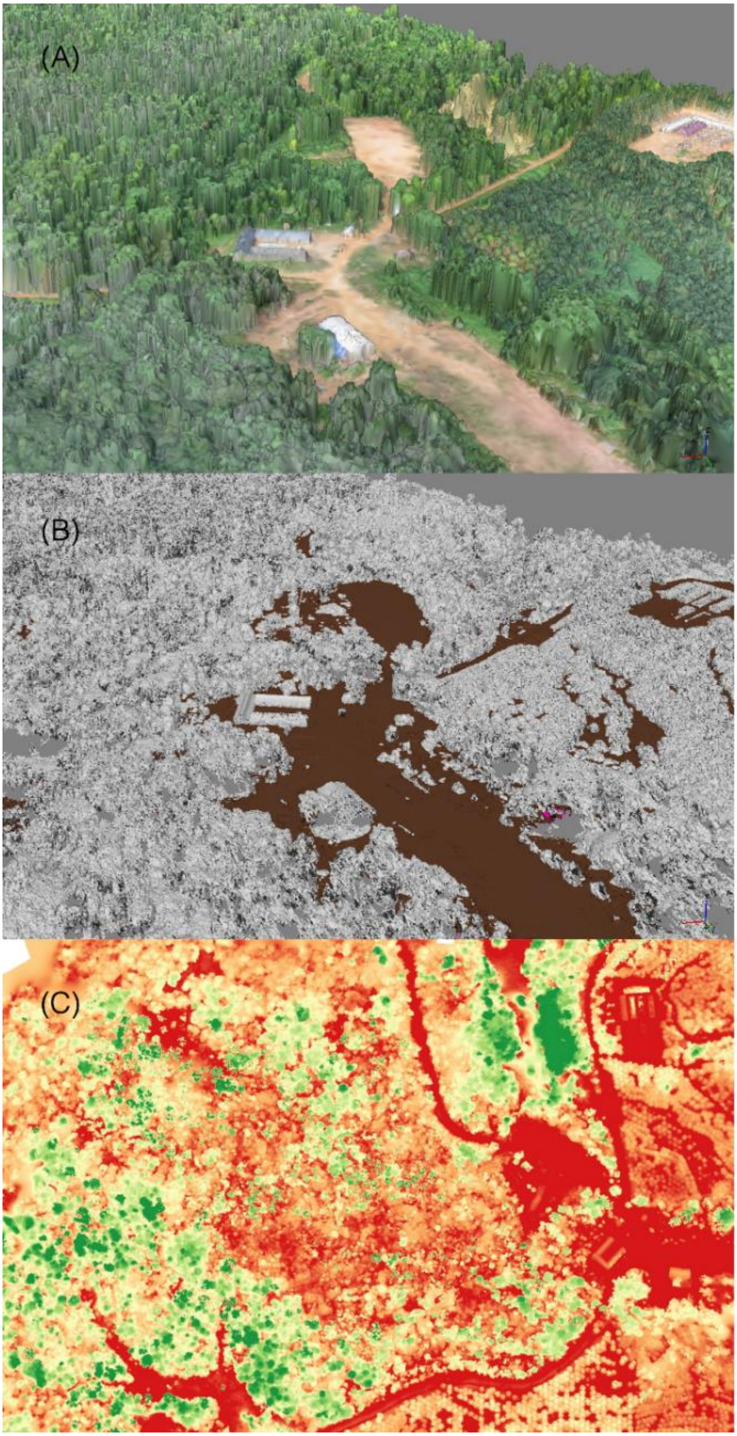

Figure 12.3 - A 3D model of regenerating secondary forest and oil palm at Hutan Harapan, Indonesia, produced using Structure from Motion (SfM):-

(A) The forest surface is shown in true-colour, reconstructed from UAV imagery.

(B) A false-colour image shows the result of automated ground classification (ground points are brown; non-ground points are white).

(C) The canopy height model produced via subtraction of the ground elevation from the model surface.

Figure 13.1 A bat acoustic monitoring station; a bat detector is kept in the box (Photo: Sara Bumrungsri)

Figure 13.2 A heterodyne bat detector (left) and a time expansion bat detector (right) (Photo: Sara Bumrungsri)

Chapter 13

AUTO-MONITORING WILDLIFE RECOVERY

George A. Gale[1] and Sara Bumrungsri [2]

ABSTRACT

Wildlife monitoring during forest restoration addresses such questions as: What species re-colonize or disappear from restored areas? How many individuals are present? What are the population trajectories? In this review, we focus on issues related to automating surveys of forest birds and mammals, particularly bats. For both birds and mammals, the need to automate data collection and analysis is clear, but several constraints must be overcome, before such automation becomes practical, compared with labour-intensive, conventional methods. Currently, wildlife species can be recognized and their abundance estimated by using audio recording and photography. However, species recognition software, using audio data, generally performs poorly, compared with humans, particularly under field conditions, where such systems fail to distinguish multiple overlapping calls and separate them from interfering background noises. Similarly, for images, highly variable lighting and lack of clarity of camera-trap images often confuse auto-recognition software. Nevertheless, automated systems continue to improve, and it is likely that they will achieve parity with humans in the foreseeable future. In the near-term, they will have the ability to save considerable amounts of time, by searching through large numbers of files, to narrow searches for particular species and transmitting such files wirelessly over networks. Furthermore, outside of cellular network coverage, drones can be used to collect image or audio data from wireless devices in the field. Thus, while these techniques are currently far from being highly accurate, inexpensive and practical for broad-scale surveys, it is not difficult to imagine a future when assessments of the wildlife recovery that is expected to occur with forest restoration will become increasingly more automated.

***Key words*:** wildlife surveys, automated analyses, bat detectors, species recognition

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OBJECTIVES OF MONITORING

Wildlife monitoring has a long history, dating back to the 1890's (PETERSEN 1896). Wildlife monitoring typically starts with the basic question "how many individual animals are there in a population?" And if we are able to answer this question through time, then it is possible to address questions like "what is the trajectory of the population (declining, increasing, or stable)?" In the context of forest restoration, we need to determine: Which species have recolonized the restoration sites? And what are their relative abundances? Hence, we can answer questions regarding the relative representation of different feeding guilds, particularly frugivores that are likely to disperse seeds into regenerating sites, and perhaps threatened species.

Such questions are particularly pertinent, because community structure changes markedly, as vegetation regenerates from relatively open, perhaps mostly weedy plants, to closed canopy forest. More recently, occupancy, which uses presence/ absence data, to assess the proportion of sample sites occupied by a target species, can also be used to monitor wildlife. Such methods may be particularly useful for broad scale, long-term assessments (VAN STRIEN et al., 2013). While the basic techniques of wildlife monitoring are relatively straightforward, several issues complicate the process such as: observer bias (BETTS et al., 2007), imperfect detectability (MACKENZIE et al., 2002) and particularly, the prohibitive costs of sampling over large spatial and temporal scales, at sufficiently fine resolutions (APPLEGATE et al., 2011). Another complication is that species identification in the field and even from camera-trap photographs often requires extensive training and/or experience. Automation of survey processes would reduce some of these complications.

Which wildlife species to monitor?

Although monitoring a small set of species, as indicators of forest recovery, has some drawbacks (CARIGNAN & VILLARD, 2002), birds have been used widely because they provide critical ecosystem services (particularly seed dispersal), respond rapidly to change, are relatively easy to detect and may reflect changes at lower trophic levels (e.g., insects, plants) (SEKERCIOĞLU et al., 2004). Mammals can also be useful indicators of ecosystem health, hunting pressure (KIFFNER et al., 2014) and seed dispersal potential, particularly bats (SRITONGCHUAY et al., 2014). However, mammals are far more difficult to survey than birds—as most do not vocalize frequently (except bats and some primates). They often occur naturally at low densities and they are frequently nocturnal. In this review, we focus on forest birds and mammals, including bats. For both birds and mammals, the need to automate data collection and analysis is clear, but several constraints must be overcome, before such automation becomes practical, compared with labor-intensive, conventional methods.

CURRENT STATE OF THE ART

Birds: species identification

For birds, one of the main constraints is reliable species identification. In tropical forested habitats, 90-95% of bird detections are by ear (GALE et al., 2009), requiring extensive experience. Even in more open habitats, a significant percentage of bird identifications are by sound rather than sight. However, the complexity of bird song, 'background' noises (present in most habitats) and multiple overlapping songs that occur in many bird communities make automated species identification a challenging task. Interestingly, automation of bat species recognition is far more advanced (SCOTT, 2012) (see below). For the purposes of thinking about automated sound analysis, there are at least five broad categories of discrete sound unit shapes that compose bird sounds: i) segments with constant frequency, ii) frequency-modulated whistles, iii) broadband pulses, iv) broadband with varying frequency components and v) segments with strong harmonics (BRANDES, 2008). If we think of those discrete bits of sound as syllables, then this complexity can range from simple repeated sequences of syllables to complex sequences of syllables with patterns that rarely repeat. We can add to this complexity field situations that make detection and classification more difficult such as when encountering duets, choruses of overlapping songs, intentional call masking or mimicry. Finally, difficulty in creating automated classifiers can arise from species that have regional dialects, very large song repertoires and even improvisational songs (BRANDES, 2008).

Overall, there are several problems with identifying all species present in noisy recordings, containing multiple, simultaneously-vocalizing birds (CHU & BLUMSTEIN 2011). A related problem is detection of one or a few target species (BARDELI et al., 2009), amidst other sources of noise, including other birds, and the detection of birds that make a particular type of call (e.g., tonal sounds) (JANCOVIC & KOKUER, 2011).

Automated analysis of bird sounds

The analysis process has two primary parts: i) call-feature extraction and ii) call classification. The choice of which features to measure depends mostly on the structure of the target calls, whereas the choice of the classifier depends on the way in which the feature measurements distinguish the various types of target calls (BRANDES, 2008). For example, features may include call duration, highest frequency, lowest frequency, loudest frequency, average bandwidth, maximum bandwidth and average frequency slope.

An entirely different approach is to use stochastic sequence modelling techniques to classify sounds, based on short-time measurements of sound features and how these features change in time. This is accomplished with hidden Markov models (HMM), a technique widely used for human speech recognition (TRIFA et al., 2008). However, perhaps the most common problem for automated identification of bird sound recorded in natural settings is background noise. It not only limits bird song detection, but also cause misclassifications (BAKER & LOGUE, 2003). The most common method for dealing with noise is to limit the sound analysis to the frequency bands where the target sounds are found by using band-pass filters. Unfortunately, these methods can also eliminate many of the target sounds if they overlap the high noise part of the spectrum (BRANDES, 2008).

Relatively recently, a multi-instance multilabel (MIML) framework for supervised classification has been used (ZHOU & ZHANG, 2007). The main idea of MIML is that objects to be classified are represented as a collection of parts (referred to as a "bag-of- instances") and are associated with multiple class labels (BRIGGS et al., 2012). In this application, the objects to be classified are recordings, the parts are segments of the spectrogram, corresponding to syllables of bird sound, described by a feature vector of acoustic properties and the labels are the species present (BRIGGS et al., 2012). All supervised-classification algorithms require some labeled training data to build a predictive model. A major advantage of MIML is that the only training data required is a list of the possible species present, rather than a detailed annotation of each segment, or training recordings, containing only a single species (which is required in most prior work) (SELIN et al., 2007). For recordings containing multiple, simultaneously-vocalizing bird species, it is less labor intensive to construct the former type of labels (BRIGGS et al., 2012).

The accuracy of such methods is still relatively low, compared with conventional techniques with human observers. For example, researchers using MIML had 20% false positives and 35% false negatives in 20 trials containing one to four species per trial, with a total of 13 possible species, (BRIGGS et al., 2012). Other methods, using complex descriptive statistics successfully recognized 317 out of 384 (82.5%) calls correctly for one species and 177 songs were correctly discovered out of 230 (77.0%) of a second species (POTAMITIS et al., 2014). Although specific accuracy relative to standard human observers appears to be lower for these automated techniques, overall, automatic species recognition can considerably reduce the search time for a human observer, when searching through thousands of audio files containing many different species (POTAMITIS et al., 2014).

Individual recognition

TERRY & MCGREGOR (2002) successfully used and compared three basic types of neural networks to identify individual Corncrakes (*Crex crex*). Since Corncrakes have calls that consist of broad-band pulses, with distinct timing, they found that the pulse-to-pulse timing is the most important feature to measure. Others, working with the same species, also found that they could assess the probability as to whether two calls belonged to the same individual or not, but definitive identification was not possible, if the number of individuals was not known beforehand. This was also shown in other species (EHNES & FOOTE, 2015). Furthermore, individual recognition can be used to estimate population sizes, using a mark-recapture framework (STEVENSON et al., 2015).

Occupancy and abundance estimation

Recent studies have demonstrated that species abundances of both birds (DAWSON & EFFORD, 2009) and frogs (STEVENSON et al., 2015) can be obtained using acoustic detection.

Hardware for automated bird recording

The basic components of hardware for use in automated recording of bird sound are a microphone, audio recorder, power supply, a mechanism for initiating and ending recordings and a weather-proof housing for the equipment. The first and simplest approach is to design a scheduling timer through a hardware interface to control a stand-alone commercial recorder. A second approach is to write software for a programmable recording device, such as a personal digital assistant (PDA) or a smart phone (BRANDES, 2005). The third and most complex approach is to develop recorders with single board computers (FITZPATRICK et al., 2005). Furthermore, in theory, recorders could be deployed into the field by UAVs as some are sufficiently lightweight (<100 g) (FURNAS & CALLAS, 2015).

BRANDES (2008) recommended that with automated recorders, omni-directional microphones could be used instead of directional microphones, because it is not possible to know *a priori* from where sounds will originate. Single-element, omni-directional microphones can be effective, but using a small array of microphones to create a more sensitive beam-pattern can increase effectiveness e.g., the linear 16-element microphone array (<15 cm in length), designed by the Bioacoustics Research Program at the Cornell Lab of Ornithology for use with their ARUs (autonomous recording units). They are most sensitive to sound around the axis of the microphone array and least sensitive in the direction pointing from each end. By placing this microphone array in the canopy hanging downward, it is sensitive to sound originating from any direction within the canopy. A second approach to improving omni-directional microphone gain is to use a specially designed waveguide to collect and amplify the sound before it reaches the microphone element. For further details see BRANDES (2008).

Software for automated bird recording

The review by BRANDES (2008) made several suggestions regarding organizations that provide software for acoustic sampling. A few commercially available software packages are used to analyze and develop automatic detection of bird sounds. The Extensible Bioacoustics Tool (XBAT) developed and distributed by the Bioacoustics Research Program at the Cornell Lab of Ornithology, has been particularly useful in developing avian sound-recognition algorithms (FIGUEROA & ROBBINS, 2008). It runs as a toolbox within the MATLABH mathematical programming environment. Other relevant software available includes Song Scope, sold by Wildlife Acoustics and SyrinxPC, provided by the University of Washington.

List of Web Addresses relevant to acoustic sampling (from BRANDES, 2008):

1. Borror Laboratory of Bioacoustics https://blb.osu.edu/
2. Cornell University’s Bioacoustics Research Program http://www.birds.cornell.edu/brp/
3. Hidden Markov Model Toolkit http://htk.eng.cam.ac.uk/
4. Macaulay Library of Natural Sound http://macaulaylibrary.org/
5. Oldbird, Inc. http://www.oldbird.org
6. River Forks Research Corp. http://www.riverforks.com/
7. Wildlife Acoustics, Inc. http://www.wildlifeacoustics.com/

CURRENT STATE OF THE ART

Bats: species recognition and automated species classification

The main constraint when studying bat communities is the difficulty of obtaining visual observations. Furthermore, bat calls are mostly inaudible. Thus, before acoustic sampling became possible, the most reliable species records were obtained by capturing bats in mist nets or harp traps. For thinking about automated species recognition, bats can be divided into two groups: fruit/nectar- eating bats and insect-eating bats. Old World, fruit/nectar bats can be identified to genera by their external morphology, especially their face, so camera trapping is needed. On the other hand, species of insectivorous bats, which produce echolocation calls, can be identified using echolocation call analysis.

Automated recognition and monitoring of insectivorous bat species is plausible because they emit echolocation calls for navigation and communication. These calls are characteristic and often species-specific. Compared with birdsong, bat echolocation calls are simpler and easier to identify using automated systems. Typically, bat calls can be classified into two types: i) quasi-constant frequency and ii) broadband frequency-modulated. Harmonics are usually present in bat calls and the harmonics with maximum energy (seen from spectrograms) are used for species identification. Similar to birds, automated monitoring requires recording and analyzing the echolocation calls. A bat detector, which converts inaudible (>20 kHz) calls to the audible range (<20 kHz), is used to record bat calls. During the last two decades, acoustic bat surveys, using bat detectors (Fig. 13.1 & Fig. 13.2), have been widely used to study distributions, activity levels and habitat use and to monitor population trends of bat species of concern, both at local and regional scales (WALSH et al., 2004). Bat detectors can also be used with canopy-foraging species and bats which fly higher above the ground, provided their calls are loud enough. However, bat detectors have their drawbacks. They cannot determine the number of bats from the number of calls produced. Thus, a relative bat activity index is used, instead of the number of bats present. Researchers use the number of ‘bat passes’ to index relative abundance. In addition, acoustic sampling is much less effective for bats that produce faint calls (e.g., small gleaning species). Thirdly, some nocturnal insects (e.g., cicadas), which produce high frequency noises (up to 50 kHz), may partly interfere with bat acoustic sampling.

Hardware for detecting bats

There are four types of bat detectors: heterodyne (Fig. 13.2), frequency-division, time-expansion (Fig. 13.2) and full-spectrum.

Heterodyne bat detectors (like radio-receivers) tune to a particular frequency (of bats). If flying bats produce such a frequency, the apparatus detects it. It is the most sensitive of the detectors and can register very weak signals, but is limited to a narrow frequency range. Thus, heterodyne detectors are useful for monitoring single species, but it is usually not possible to save frequency information.

Frequency-division detectors use a broadband technique (i.e., the entire ultrasonic range is transformed at all times). The transformed frequency is usually one tenth of the original frequency. Thus, calls of 70 kHz in 5 ms generate an audible output at 7 kHz in 5 ms. They are less sensitive than heterodyne detectors, as they have a minimum threshold level. Signals below the threshold are not transformed. However, frequency division bat detectors provide more information about recorded calls and they can be used for sound analysis. The fundamental frequency is retained and pulse duration and other temporal parameters can be measured. Output is in real time and can consequently be used to continuously monitor bat activity, although some physical information of the calls is lost.

Time expansion detectors also use a broadband technique. They sample and digitize a signal and play it back over an expanded time. The time expansion factor can vary from 10-32, but 10 is commonly used. Since it plays back at slower speeds, the output frequency is lower and the pulse is longer. In using, for example, a 10x time expansion bat detector, a call of 70 kHz and 5 ms will play back at 7 kHz and 50 ms. All the physical properties of signals including the harmonics are virtually preserved and output is excellent for sound analysis. Once expanded, calls can be recorded via a recorder or directly recorded by a computer. This type of bat detector is suitable for studies of social behavior, as well as species identification. However, this system cannot record during playback. Thus, it cannot continuously monitor bat activity. With a 10x expansion, the system samples only 7-9% of the available time.

Full-spectrum detectors record all frequencies. They sample at very high rates to capture all signal information and output it in real-time, so we get not only the details of call structure (as with time expansion systems), but also the real-time continuous monitoring (as with frequency division systems). They enable a very detailed analysis of the sound and a clearer sonogram, compared with frequency-division systems. Full-spectrum detectors are often used for passive monitoring, where a researcher does not need to be present to save recorded calls.

Although frequency-division detectors produce files that are approximately one tenth the size of those produced by time expansion detectors, their recorded calls are much less informative; hence species identification is more difficult, especially where calls are less well-documented or with relatively higher species richness. In some models, time expansion bat detectors provide a noise triggering option (allowing the device to start recording as soon as sound is detected), to save recording space. In most models, an on-off timer is provided, to save battery power, allowing batteries to last up to a month. The most fragile part of these bat detectors is the microphone, which is sensitive to humidity. Generally, most models of frequency division, time expansion and full-spectrum bat detectors use directional microphones. However, some models offer omni-directional microphones, which are less sensitive. Prices vary considerably; although heterodyne detectors are relatively inexpensive (under US$ 100 as of the year 2016), other types are generally higher in price, sometimes more than US$ 1,000.

Manual and automated analysis of bat sounds

Only recently has automated analysis of bat calls been available. However, manual call analysis is still needed for many areas of the world because call databases for automated call identification software are available only for bats in Europe and North and South America. Commonly-used manual call-analysis software packages include Batsound and Avisoft. Recorded calls are filtered, to delete background noise, and then six parameters, from the call harmonics with the most energy, are measured: call duration (ms), frequency at maximum energy, frequency at half of the call's duration, frequency at beginning of call and inter-pulse interval (PREATONI et al., 2005). Manual call measurement is time-consuming. Fortunately, up to 19 characteristics of an echolocation call can be automatically measured, with the free software available in the program R (SILVA, 2014). This identifies calls using discriminant function analyses (DFA) to compare recorded calls with those of known species (reference calls). Another call-identification technique uses artificial neural networks (ANNs). Neural networks are "taught" to recognise call characteristics of known species and when calls of unknown species are submitted, ANNs can classify them. This approach has been successfully used for dolphins and bats. PARSONS & JONES (2000) achieved an 87% success rate when identifying 12 bat species in Britain (with success rates for each species ranging from 75% to 100%). They also performed DFA, but the percentage of correct identification was lower; 79% overall. Similarly, RUSSO & JONES (2002) achieved an 82% overall success rate, using DFA to identify 20 bat species in Italy. PREATONI et al. (2005)

compared DFA with ANNs to distinguish between bat species in the family Vespertilionidae. DFA had a higher correct identification rate, but both were 100% correct when identifying species of the Rhinolophidae. The efficacy of both DFA and ANNs depend on the quality and breadth of training data since they both “force” unknown calls into the groups predefined by such data (JONES et al., 2000).

For automated call analysis, several automated classifier software packages are now available. These include SonoBat, Kaleidoscope Pro, Bat Call Identification (BCID), EchoClass and SonoChrio. These packages are helpful where call databases are available, such as North America and Europe. Some of them only work with call files of particular formats (e.g., zero-crossing, wave files), produced from bat detectors. However, these call files can be converted to different formats. The cost of these programs is ca. US$ 1,500. Currently, automated call classifiers have several limitations. Typically, they do not include all call characteristics in their analyses, such as amplitude-time data. Consequently, they only work well with species that have distinct frequency characteristics. They are most useful where the call characteristics of every species in a community are well-understood. In addition, results from automated classifiers still need manual verification.

In summary, automated classifiers are still in their infancy and more research and development are needed to truly automate bat surveys (review by RUSSO & VOIGT, 2016).

Bat species abundance/density

As bat detectors are not able to distinguish individual bats, an index of relative abundance, based on the number of recorded calls or ‘bat passes’ of each species, is used. A bat pass is defined as an echolocation call with at least two consecutive pulses. However, with the Anabat frequency-division bat-detector for example, researchers can use the number of files with calls of a particular species as an abundance index. Using this protocol, bat researchers could quantify habitat use/selection of particular bat species in restoration sites.

Internet sources for bat detectors and automated classifier software:

1. http://batdetecting.blogspot.com/
2. https://www.bats.org.uk/our-work/training-and-conferences/training-for-ecologists/using-bat-detectors
3. https://batmanagement.com/collections/software

TERRESTRIAL MAMMALS

Camera trapping

For assessing communities of medium- to large-bodied terrestrial mammals, camera trapping is the most reliable method (CHUTIPONG et al., 2014) (e.g., Figs. 13.3 & 13.4), although identification of species from photos is still problematic, because of the level of experience and expertise required (MEEK et al., 2013). Researchers have been estimating abundance of large mammals with camera traps for more than two decades (KARANTH & NICHOLS 1998), particularly large cats such as tiger (*Panthera tigris*) (KARANTH & NICHOLS, 1998). However, extensive manpower is needed to check and retrieve data from traps. Currently there are study plots where cameras have been networked to run continuously, but areas sampled are small (~10 ha) (KAYS et al. 2009). Some commercially available trail cameras have wireless support, such that photos and video can be sent through text messages and email within 90 seconds after an animal has passed triggering the trap, but they require a cell phone signal. To overcome this limitation and allow remote data collection from traps outside the ranges of cellular networks, drones are being developed as “data mules”. For example, the Wadi Drone (http://wadi.io/) homes in on Wi-Fi signals emitted by camera traps and circles the traps until all images are uploaded to the drone, which then returns to base. The traps are powered by solar cells so no battery changes are needed. Presumably, a similar system could be used to retrieve audio files. Pattern recognition and other data management software have also been used with camera trap photos to identify species (FEGRAUS et al., 2011) or individuals within a species (HIBY et al., 2009). Drone-mounted cameras (including thermal/infrared imagery) have also been used to accurately detect some species of wildlife, although over relatively small areas (Christie et al. 2016).

THE NEXT STEPS

Currently, wildlife species can be recognized and their abundance estimated using automated processes, both for audio data and images. However, species-recognition software generally performs poorly compared with humans, particularly under field conditions, where multiple calls overlap and background noises interfere with and obscure audio data, and highly variable lighting and limited image clarity from camera traps confuse image-recognition systems. Nevertheless, automated systems continue to improve and it is likely that they will achieve parity with humans in the foreseeable future. In the near-term, they will have the ability to save considerable amounts of time by searching through large numbers of files to narrow searches for particular species for example, and such files can be transmitted wirelessly over networks. Furthermore, outside of cellular network coverage, drones can be used to collect image or audio data from solar powered, wireless devices in the field. Thus, while these techniques are far from being highly accurate, inexpensive and practical for broad-scale surveys, it is not difficult to imagine a future where assessments of the wildlife recovery that is expected to occur with forest restoration will become increasingly more automated.

FURTHER DISCUSSION

One of the important issues for automated wildlife monitoring is how to improve the accuracy of automated systems, such that they are on a par with or even less biased than human observers. One critical set of experiments/research areas towards this goal is field validation. Field validation essentially requires placing automated devices where target species and their abundances are precisely known. Although such sites are rare, particularly in the tropics, they do exist (e.g., Gale et al. 2009). We therefore suggest that a rich opportunity for collaboration is possible between researchers who are interested in automated monitoring and those running long-term wildlife-monitoring sites.

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Figure 13.3 - A Large Indian civet *Viverra zibetha* a common and regionally important seed disperser, photographed with a trail camera in Thung Yai Naresuan Wildlife Sanctuary (Thailand), April 3, 2011. Populations of species with unique, individual markings can be monitored during restoration using automatic camera traps (photo: Wanlop Chutipong).

Figure 13.4 – Thai researchers setting a camera trap (photo: Wanlop Chutipong)

Figure 14.1 - We need to get communities involved not only in technologies but also, in planning all aspects of restoration.

Figure 14.2 - Safety is most important issues when promoting drone use. Here, village children flee as the eight propellers of a wayward prototype double quadcopter career towards their shins.

Chapter 14

Social, Economic and Legal Issues of Automated Forest Restoration

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ABSTRACT

Practitioners often concentrate most on the technical aspects of forest restoration and less on the social aspects, whilst often ignoring legal aspects. Social considerations include involving all stakeholders in planning, tree planting or tending natural regeneration, and monitoring. The most important legal considerations are usually concerned with land tenure. Automation will most probably further complicate both social and legal aspects of forest restoration. Social acceptability of the use of unmanned aerial vehicles (UAVs) and the other technologies, described throughout this volume, will undoubtedly be subject to much debate. Communities may well develop their own "no fly zones" such as sacred sites etc. Use of UAVs is subject to, and may be restricted by, a rapidly growing number of new regulations, particularly those focussing on the critical issues of safety and personal privacy. Social norms and laws vary widely among countries and are rapidly evolving. Therefore, this review highlights just some of the currently emerging socio-economic and legal issues that may impact the implement-ation of automated forest restoration (AFR). Those proposing novel AFR methods, should consider such issues simultaneously with the development of new technologies, so that AFR projects can be planned and implemented with minimal legal problems and social disruption.

Key words: community, socio-economics, sacred sites, unmanned aircraft systems, security, privacy, drone law

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SOCIAL AND LEGAL DIFFERENCES BETWEEN CONVENTIONAL AND AUTOMATED FOREST RESTORATION (AFR)

The science and technology of forest restoration has advanced considerably in recent years (DELLASALA et al., 2003; ELLIOTT et al., 2013). However, less attention has been paid to the legal and social aspects of such activity. DELLASALA et al. (2003) argue that, in addition to enhancing ecological integrity, good ecological restoration depends on three main principles i) sound ecological science, ii) effective ecological economics and iii) support from communities, including a motivated, incentivized, work force. When considering the automation of forest restoration tasks, new and additional cultural factors (e.g., beliefs) may come into play, for example, flying UAVs over off-limit areas, such as sacred sites, may offend some communities. Automation may also alter the economics of restoration, particularly employment of villagers in formerly labour-intensive tasks. Legal aspects, concerning land tenure, are similar for both automated and conventional forest restoration and have social dimensions, particularly the restoration of communal lands. However, the use of UAVs opens up a whole new area of potential legal problems, centred around safety and privacy concerns.

During the workshop, group discussion on social and legal issues, participants highlighted the following questions:

1. What are benefits of AFR to local communities?
2. Sense of local ownership – would local people be more or less willing or able to participate in AFR, compared with conventional forest restoration?
3. Would AFR displace local employment opportunities?
4. Would AFR open up new local training and employment opportunities, such as operating drones, manufacturing “seed bombs” etc.?
5. How might development of AFR benefit from local knowledge, e.g., knowledge of terrain, tree species used and use of local materials and services?
6. Might AFR affect local sensibilities in ways that conventional forest restoration does not, e.g., flying drones over sacred lands?
7. Would AFR skills and technologies have any spin-off benefits for local agriculture?
8. Would AFR require different models of stakeholder engagement, com-pared with conventional restoration?

SOCIAL ISSUES OF AUTOMATED FOREST RESTORATION

Socio-economic indicators for forest restoration

Effective forest restoration projects have both ecological and socio-economic benefits. Ecological benefits include biomass (and carbon) accumulation, the diversification of forest structure and the recovery of biodiversity and ecological functioning, with the consequential return of a vast range of forest products and ecological services, both to local communities and downstream stakeholders. Socio-economic benefits flow from revived forest products and services, either when they are perceived to have socio-political values (e.g., strengthening land tenure) or when they start to yield cash income. EGAN & ESTRADA-BUSTILLO (2011) developed indicators for assessing the socio-economic outcomes of forest restoration projects. The most highly rated indicators were related to job creation, community stability, economic impacts and collaborative participation in forest restoration processes.

Immediate restoration costs (e.g., planting stock, transport, labour, fertilizer, etc.) play a major role in influencing the type of restoration strategy that local stakeholders select. The implementation costs of forest-landscape restoration are highly site-specific (REUBEN, 2015). AFR, reduces some restoration costs (e.g., labour, nursery running-costs etc.), whilst also generating new costs. UAVs are currently quite expensive and they have short life spans, but prices are declining rapidly and durability is getting better. Entry-level quadcopters, with very basic cameras, can be bought for less than $100, whilst more sophisticated drones, with high resolution cameras and advanced navigational and object-avoidance technologies, start at around $1,000. Prices depend on flight time, rotors, size, weight, camera quality and control/navigation systems. The costs of permits to fly should also be factored into overall costs (ATTKISSON, 2016). Using drones, to drop seeds passively into inaccessible restoration sites, could be achieved at relatively low cost, probably more cheaply and safely than employing human labour to plant trees. However, more complex AFR tasks, such as seed collection or weeding, depend on advanced imaging or sensing technologies, which are still very expensive.

Land tenure

Land tenure is probably the most important socio-legal consideration when planning all forest restoration projects, whether conventional or automated. Involving land owners (and all those who may have other rights to the land or control access to it) in forest restoration planning and implementation ultimately determines the long-term fate of restoration projects. This is because those stakeholders with local land rights are most immediately affected by forest restoration, either positively (e.g., benefits from forest products and environmental services) or negatively (e.g., crop production foregone) (OVIEDO, 2005). However, AFR requires additional considerations concerning land. Space will be needed for UAV take-off and landing, storage and maintenance facilities, if not on the restoration site itself, then a short distance away.

Figure 14.3 – UAV technologies have agricultural applications. Hmong villagers (in northern Thailand) showed great interest during a demonstration of a crop-spraying UAV, during the workshop

Collaborative participation

In general, participation depends on people's interests in forest restoration. With conventional forest restoration, getting people to work collaboratively is challenging, because much of the work involves hard labour. Human labour is required, from seed collection, to tree planting and maintenance. On tree-planting days, it is common to see some people simply giving up, when carrying baskets of seedlings up steep slopes, leaving such arduous tasks to a few strong people.

On the other hand, for AFR, use of UAVs requires highly trained personnel. For villagers, the learning curve is steep. If they are interested in AFR, they will have to invest lot of time in training, before being able to operate AFR technologies. Despite the learning challenges, UAV technologies are likely to stimulate participation in forest restoration, because of their novelty and entertainment value (Fig. 14.1). Villagers may also recognise that training in UAV operation has applications in agriculture. One experience we had during the workshop was that villagers showed great interest when small UAVs that are capable of spraying crops were demonstrated (Fig. 14.3). The villagers were willing to let the pilots fly UAVs over their land and demonstrate their capabilities. The attractiveness of the new technologies may be able to promote collaborative participation and acceptance of forest restoration projects.

Cultural no-fly zones?

Different countries impose various airspace restrictions. Restricted areas (no-fly-zones) typically include civil and military airspace (Federal Aviation Administration, 2016) and they tend to be imposed near airports, hospitals, power plants and around the venues for national and/or international events. It is mandatory for UAV operators to be aware of where not to fly and flight software often blocks take off in such areas. In addition to no-fly-zones, recognized by the government, some areas are spiritually sensitive and regulations regarding UAV flights have not been established.

Sacred spaces can include man-made religious monuments (e.g., temples, burial grounds) or natural places of religious or spiritual significance (e.g., mountains, rivers etc.) (Gale, 2005). About 15% of the world’s surface is considered to be sacred (Alliance of religion and conservation, 2016). Certain actions are sometimes prohibited in such holy or sacred places. For example, in some cultures, it is considered inappropriate for women to enter certain sacred sites. Consequently, the likely cultural reactions to the possibility of UAVs flying near or over such sensitive areas must be carefully explored with local stakeholders when planning AFR projects (Fig 14.4). Furthermore, certain tree species may also be considered of spiritual significance, depending on local beliefs. Some may be regarded as the home of good or evil spirits, whilst others may yield products that are used in religious rituals. This may affect species choices, when planning which tree species to plant, whether seeded from drones or planted as seedlings.

Figure 14.4 - A sacred ground has a spiritual significance. In this photo, a Hmong villager performs a ritual in the forest. AFR practitioners must consult with local stakeholders to determine which practices are appropriate when considering flying over or implementing other forest restoration tasks in or near sacred sites.

Tapping into indigenous knowledge for (automated) forest restoration

In additional to helping with the cultural and spiritual aspects of species selection, local villagers should also be involved in other aspects of tree species selection. If following the framework species approach, the selected tree species should have reasonably high survival and growth rates, when planted out in the hot dry sunny conditions that typify open, deforested sites. They should have dense spreading crowns, to shade out weeds, and produce edible fruits or nectar-rich flowers to attract seed-dispersers. If such information about local native forest tree species is incomplete, indigenous knowledge can be of immense value. Local people know first-hand which tree species tend to recolonize abandoned fields (fast-growing pioneers), which are most attractive to seed-dispersing wildlife and optimum seed collection times. They are also very much aware of which species have local economic uses that would increase the acceptability of restoration projects among the local population (ELLIOTT et al., 2013). Indigenous knowledge of herbs and grasses may also play a part in developing effective auto-weeding methods. Local people may become involved in helping to develop weed species recognition software and they may help with the development of weeding regimes that draw on their knowledge of weed phenology. Thus, even though AFR will undoubtedly be based on cutting-edge technologies, traditional local knowledge has much to contribute and mechanisms must be developed to facilitate dialogue among scientists, engineers and villagers beginning with the development and planning stages of AFR (Fig. 14.5).

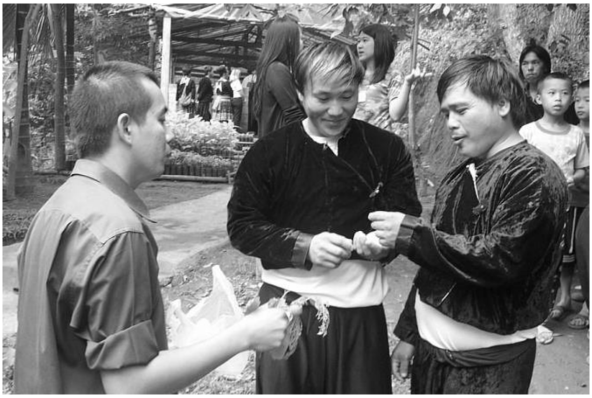


Figure 14.5 – Working with indigenous people enables local knowledge transfer.

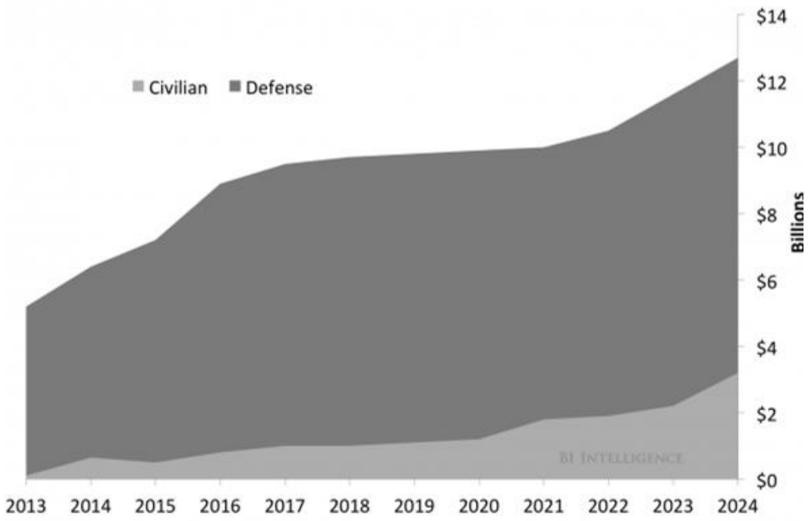
Pros and cons of conventional and automated forest restorations

Introducing new technologies that may replace conventional methods of any activity requires time for people to learn, adjust and adapt. Even though UAVs have been used for various purposes (ranging from aerial photographing to parcel delivery), their use for forest restoration is new. Therefore, the development and testing of new AFR technologies should occur concurrently with exploration of the social, political and economic aspects of using such technologies. This not only increases the chances that modern technologies will be accepted by local stakeholders, but might also provide training and employment opportunities for villagers and shorten the length of time needed for adjustment and adaptation.

LEGAL ISSUES CONCERNING USE OF UNMANNED AERIAL VEHICLES (UAV)

The rapid rate of development of UAV technologies continues to outpace the formulation of legal regulations. Historically, UAVs have been primarily used for military purposes e.g., for combat (bombing) and intelligence gathering. Hence, their use has been subject to military regulations. However, as the technology becomes cheaper, more easily available and user-friendly, UAVs of various sizes are now available for commercial and recreational (civilian) use. Worldwide, at least 441 companies are involved in UAV manufacturing (UAV Global, 2016). The civilian UAV market is predicted to grow by 19% annually from 2015 to 2020 (BI Intelligence, 2015). Increased use of UAVs, since 1980 (Fig. 14.6) has given rise to concern about two important issues: i) safety and ii) privacy.

Figure 14.6 - Forecast of global growth of the civilian and military UAV markets (Sources: Teal Group, BI Intelligence Estimates, Michael Tascano)



YEAR

Safety

Safety issues include UAVs injuring people (Fig. 14.2) and damaging aircraft, which in turn potentially threatens lives. The safety issues reviewed here exclude those posed by military drones, which often target people. UAVs may crash into and injure people unintentionally, when batteries or guidance systems fail, or when structural failure renders the drones uncontrollable. Intentional injuries can occur when controllers deliberately fly UAVs into people or aircraft. In recent years, use of UAV-mounted cameras to film public sporting events has become commonplace, but UAVs pose hazards to both athletes and bystanders. In 2013, a drone (1.2 m across), fell into an audience stand and hurt five people at a Bull Run event in Virginia, USA (WEIL, 2013). In 2014, an Australian triathlete was struck on the head by a crashing drone, while running a race in west Australia. The drone was operated by a videographer, who was filming the event (DOYLE, 2014).

Human factors play significant roles in UAV crashes (DEGARMO, 2004). UAV crashes may become less likely as UAV technologies become more reliable and operators gain more experience. However, there is no consensus on standard skill levels that should be required of UAV operators for commercial use (DEGARMO, 2004).

In addition to injuring people, UAVs flown near airports and/or flight paths threaten aircrafts and their passengers. From 2014 to 2015, there were 764 close-call incidents (i.e., a situation in which a collision almost happens) between UAVs and other aircraft (up to August 9th 2015) in the USA (FEDERAL AVIATION ADMINISTRATION, 2015), although only 27 were incidents reported by civilian aircraft pilots; the rest involved military aircraft (JANSEN, 2015). In the United Kingdom (UK), there were 23 close-call incidents around airports during six months in 2015 (April to October). One of the most recognized close-call incidents occurred at London's Stansted Airport in September 2015. The pilot of a Boeing 737 passenger jet reported seeing a 2-meter-wide-UAV, which passed less than five meters above the aircraft's path in controlled airspace (TOPHAM, 2016). Other close-call incidents, involving UAVs, included sightings of small UAVs, when planes were taking off or approaching the runway (e.g., PIGGOTT, 2014; TOPHAM, 2016; UNITED KINGDOM AIRPROX BOARD, 2016). As of February 2016, the number of close-call incidents involving UAVs was six out of a total of 10 close-call incidents (UNITED KINGDOM AIRPROX BOARD, 2016).

Privacy

Privacy concerns are also associated with the use of UAVs, since most of them carry cameras. Before the advent of UAVs, manned aerial vehicles had been used for land mapping, aerial photography, area surveys etc., usually operating at 150 meters or higher above ground level in populated areas (FEDERAL AVIATION ADMINISTRATION, 2015). Therefore, although such aircraft were undoubtedly capable of invasion of privacy, their presence was less perceptible by people on the ground compared with drones. In contrast, UAVs can be operated just a few metres above the ground. They can take really close up and detailed images, even looking sideways into buildings. This capacity for low-altitude hovering and close-up photography has raised considerable public concern about invasion of privacy.

In 2015, a quadcopter evaded security and crash-landed on a lawn of the White House, where the president of the United States resides and works (MILLER, 2015). The UAV operator was not charged. In other incidents, people have protected their privacy by destroying UAVs that they feel have intruded. One incident that shows how threatened people feel by the presence of drones occurred in 2015 in the USA, where a man shot down a drone that was hovering above his property, believing that the UAV was spying on his daughter (VINCENT, 2015). It is therefore likely that public concerns over invasion of privacy will significantly affect the evolution of drone laws and regulations.

Figure 14.7 – Public safety and privacy are less of a concern in unpopulated areas, such as an abandoned agricultural land. In the figure below, a UAV pilot sets up a ground station for flight control systems in an open area to test an aerial seedling device.

Safety and privacy issues of AFR

Although the use of drones for AFR is likely to be seriously impeded by broad rules and regulations, it is unlikely to pose a danger to public safety and privacy, since AFR sites are (by definition) are far from public access and populated areas (Fig. 14.7). Therefore, the use of UAVs for site surveying, seed collecting and aerial seeding is unlikely to interfere with people's activities (except for the case of sacred grounds mentioned above). However, because UAVs may fly over wildlife habitats, they may affect animal behavior. In the USA, recreational use of UAVs is banned from national parks, because of concerns about disturbing wildlife (UNITED STATES NATIONAL PARK SERVICE 2014). The response of wildlife to drones is highly variable. For example, elephants are either unaffected by them or move away, since the sound is similar to bees, which elephants naturally avoid. This response has been used in Africa to "shepherd" elephants away from crops and danger[4]. In contrast, birds of prey are threatened by UAVs and attack them (ENGELKING, 2015). Further studies of the effects of UAV operation on wildlife are needed for appropriate development of AFR technologies.

DIFFERENCES IN NATIONAL REGULATIONS ABOUT UAVs

At the international level, the UN has yet to formulate standards or guidelines about the civilian use of commercially available UAVs. Therefore, national governments have taken the initiative to create their own rules, in response to the rising growth of UAV use. Consequently, laws that control UAV use vary greatly among countries (Table 1). Countries can be grouped into three categories, according to national regulations regarding UAVs: i) no existing official regulations, ii) relaxed regulations and iii) strict/complex regulations (Table 1). Most African and Asian countries have no drone laws in effect, although some are in the process of drafting and passing such laws.

Countries with drone laws are split roughly equally between those with relaxed regulations and those with more strict or complex regulations. Less strict regulations usually cover where drones may be flown and limit the altitude at which they can be flown. For example, in Finland, drones cannot be flown higher than 150 meters above the ground (FINNISH TRANSPORT SAFETY AGENCY, 2015). Other common regulations, restrict drone flights to good weather conditions during daylight hours or stipulate how far away they must be kept from airports (e.g., LATVIA CIVIL AVIATION AUTHORITY, 2006).

Countries with relaxed regulations include, for example, Paraguay, Uruguay and Latvia. Those with stricter or more complex rules include the Philippines, Malaysia and Thailand. Such regulations usually involve registration of drones, limit their size or stipulate training of drone pilots.

In the Philippines, all UAV equipment must be registered with the Civil Aviation Authority of the Philippines (CAAP) (CIVIL AVIATION AUTHORITY OF THE PHILIPPINES, 2015). In order to operate a UAV, operators must be certified through a complex process that includes: prior practice, a training course and either a flight crew license or an air traffic control license. Military certification equivalent to operation certificates is also acceptable.

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[4] wildtech.mongabay.com/2015/05/drone-herders-tanzanian-rangers-and-researchers-use-uavs-to-protect-elephants-and-crops/

In Malaysia, UAVs must meet or exceed the safety and operational standards established for manned aircrafts. Drones are also not allowed to endanger people or property (in the same way as for manned aircraft). All UAV operators must hold a Private Pilots' License before operating UAVs and receive authorization from the Department of Civil Aviation to fly UAVs heavier than 20 kg (DEPARTMENT OF CIVIL AVIATION OF MALAYSIA, 2008).

In Thailand, UAV use is categorized into: i) recreational use and ii) research and commercial use. Use of UAVs for research requires the submission of flight plans to the authorities and the issuing of permission prior to use. Pilots must register with the Thailand Civil Aviation Authority. UAV users must also have third-party-liability insurance, with coverage of 30,000 US dollars or more (THAILAND'S MINISTRY OF TRANSPORTATION, 2015).

Table 1 - Summary of national regulations of UAV uses of top 15 countries with the most serious forest cover loss

Country (Ranking by percentage of forest loss)	Forest loss (%) (2001-2012) relative to tree cover in 2000*	Legal regulation of UAVs
Mauritania	43.8	No official regulations
Malaysia	14.8	Strict/Complex
Portugal	14.8	No official regulations
Uruguay	12.7	Relaxed
Paraguay	12.1	No official regulations
Cambodia	10.9	Strict/Complex
Latvia	10.4	Relaxed
Saudi Arabia	10.4	No official regulations
Guatemala	9.7	No official regulations
Argentina	9.2	Relaxed
Indonesia	9.0	No official regulations
Nicaragua	8.9	Relaxed
Sweden	8.4	Relaxed
Finland	8.2	Relaxed
United States	7.9	Strict/Complex

*Source: *HANSEN ET AL., 2013*

Effects of legal regulations on development of AFR

The practicality of using UAVs for AFR is affected by legal regulations. Strict, complex regulations are likely to slow down AFR development. Restrictions on where UAVs can be flown may have little impact on AFR, because the technique targets less accessible areas with low population densities. On the other hand, regulations on how UAVs may be flown may have a much more restrictive effect.

In Thailand, the law stipulates: pilots must be able to see UAVs throughout the entire duration of flights. Pilots are not allowed to use a UAVs camera for navigation i.e., autonomous flight is not allowed (Thailand's Ministry of Transport-ation, 2015). However, the regulations allow room for negotiation on a case-by-case basis. If the processes of getting permission to use UAVs and register flight plans are time-consuming, the use of UAVs in AFR research may be paralyzed.

To further develop UAV technologies for AFR, ecologists and technologists must develop mechanisms to influence policy makers – to clearly explain the benefits of AFR technologies for restoring forest ecosystems and re-establishing flows of products and ecological services therefrom. They must also be pro-active in suggesting sensible regulations that deal with the actual dangers of working with UAVs, whilst also addressing the less tangible concerns that arise from the uncertainties that surround the introduction of new technologies.

Communicating effectively with the general public will be critical in determining whether or not AFR technologies are widely adopted. When a wide range of stakeholders have been convinced of the values of AFR and of sensible, but not overly restrictive regulations, they may be able to lobby governments to enact laws that encourage and support AFR, rather than stifle it.

Box 14.1 - Additional questions to consider before planning AFR

- Are people more likely to participate in AFR than in regular tree planting?
- Who will be using AFR?
- Who could fund the research and implementation costs of AFR?
- Does local knowledge, e.g., local weather, local terrain, benefit AFR?
- Could plastic and metal, in AFR technologies be replaced by biodegradable materials?
- Who will be responsible for any accidents caused by AFR operations? e.g., herbicide drift on to crops or UAV crashes into people or buildings.

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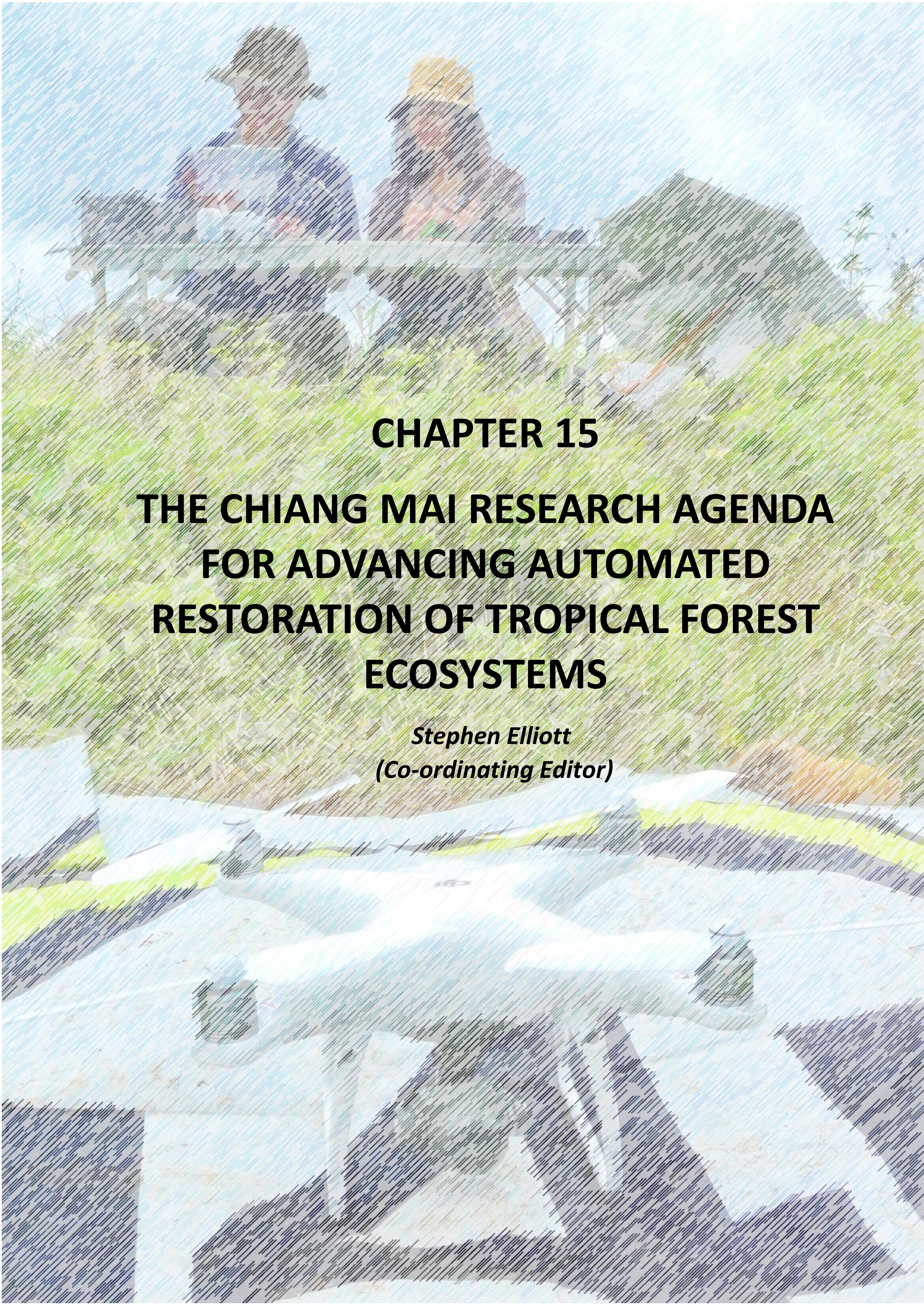

CHAPTER 15

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

The two 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, whilst achieving 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 the need for them 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 and Irina Fedorenko

RATIONAL

This topic achieved, by far, the strongest consensus at the workshop; reconfirmed during the meeting of workshop participants in Feb 2021. It covers the need to design effective seed-containing projectiles, which 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, under 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. review 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). Drone-seeding company, DroneSeed[2], reported tree establishment rates up to 37%, using compressed, fibre discs ("pucks") as projectiles, with capsaicin as a predator repellent and 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 may be required for different species (scarification, soaking etc.). However, bespoke solutions are costly. So, research towards common projectile types, scalable across various species and site conditions, would have maximum impact.

[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. Design recommendations for 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 current 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 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 more promising research areas might be to concentrate on the selection of desired tree species (or varieties) with elevated inhibitory allelopathic effects on herbaceous weeds followed by development of methods to extract and identify such allelo-chemicals 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 post-emergence 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 weedy vegetation.
2. Identification of allelochemicals as novel herbicides, which 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 by AI, using data from a combination of UAV-borne sensors.
2. To evaluate the minimum resolution and quantity of data required (e.g., RGB vs. hyperspectral), 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 and Restoration Management

Compiled by Gunter Fischer, Lisa Ong and Stephen Elliott

RATIONAL

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 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-performance 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 systems 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 the use of UAVs as 'data mules' to retrieve data from autonomous camera traps and microphone arrays in 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 lack of thermal contrast, due to heat from the ground, absorption and emission of thermal infrared radiation by the atmosphere, obscurement 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 over dense vegetation (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 humans, such as ultrasonic bat calls (see Chapter 13) or infrasonic elephant calls. Novel compression methods, can make automatic data extraction possible, and can be adapted to acoustic monitoring of a range of 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, could be set up in restoration areas to monitor 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 recordings, 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 and 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 the following 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 monitoring 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. 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 suitable 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 or 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 the use of phenocams images for monitoring growth/survival of planted trees and natural regenerants.

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 in 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 object-avoidance systems and both battery life and connectivity range (between drones and controllers) have increased substantially and continue to do so. 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 immense 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.

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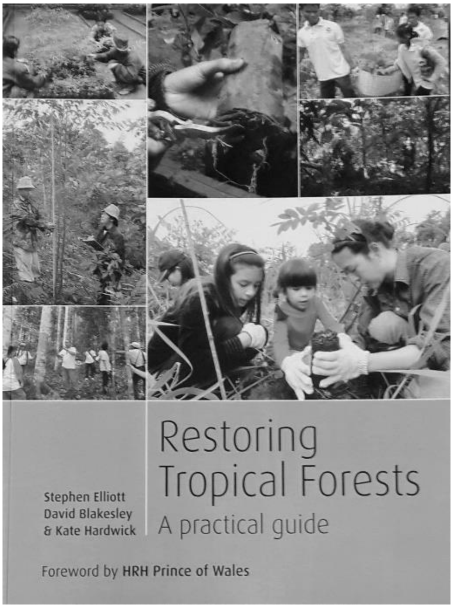
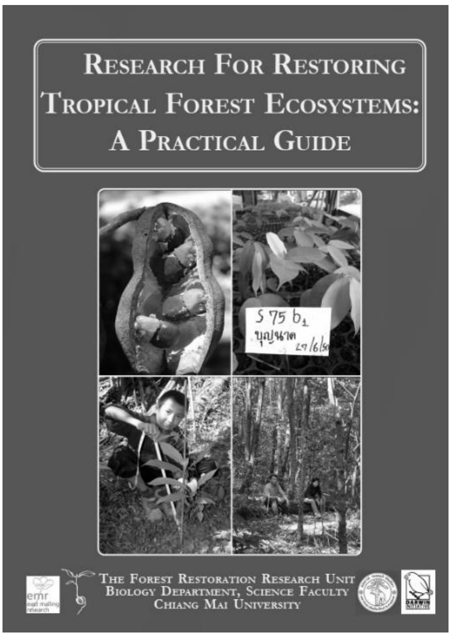


"Restoring Tropical Forests" is a hands-on guide to restoring degraded tropical forest ecosystems. Based on innovative techniques, developed by FORRU-CMU's research program, it provides clear advice and illustrated instructions on all forest restoration tasks, from site selection and survey, to planning with local communities, fund raising, running a tree nursery, planting trees, maintenance and monitoring. It is an invaluable resource for anyone involved with restoring tropical forests: practitioners, researchers, students and policy makers. Available in English, Spanish and French, it can be downloaded free from www.forru.org/library/0000152. To order hard copies please send an email to forru_cmu_th@yahoo.com.



"Research for Restoring" is a technical manual, aimed at researchers. It describes how to establish a forest restoration research unit and develop a research program to determine how best to restore tropical forest ecosystems. It details how to set up and run a research tree nursery and field-trial plot system. Techniques covered include phenology studies, seed germination trials and monitoring the performance of planted trees, biodiversity recovery and carbon accumulation. Protocols for data collection, analysis and interpretation are included. Free downloads in English, Thai, Khmer, Indonesian, Chinese and Lao are available at www.forru.org/library/0000156. To request hard copies, please send an email to: forru_cmu_th@yahoo.com.

FORRU-CMU's Free Online Consultancy Services

Want to know more about forest ecosystem restoration (auto *or* manual)? A library, structured advice and information about training services are freely accessible *to all*, through FORRU-CMU's website, including free downloads of this book and many others. Enjoy!

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Advice

Learn how to restore a tropical forest ecosystem, based on FORRU-CMU's research outputs.

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Here are the proceedings of a brainstorming workshop: "Automated Forest Restoration: Could Robots Restore Rainforests?", hosted by Chiang Mai University's Forest Restoration Research Unit. The volume comprises 14 original papers on various technologies, which could be adapted or developed to perform various forest-restoration tasks: drones, imaging technologies, artificial intelligence, bio-herbicides, GIS software, camera traps etc. It culminates in an agenda, which prioritizes research topics, aimed at research students, to advance existing technologies or create new ones, to facilitate cost-effective forest restoration, over large areas or on remote sites. Foreword by David Lamb. Available as a free download from **www.forru.org**.

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