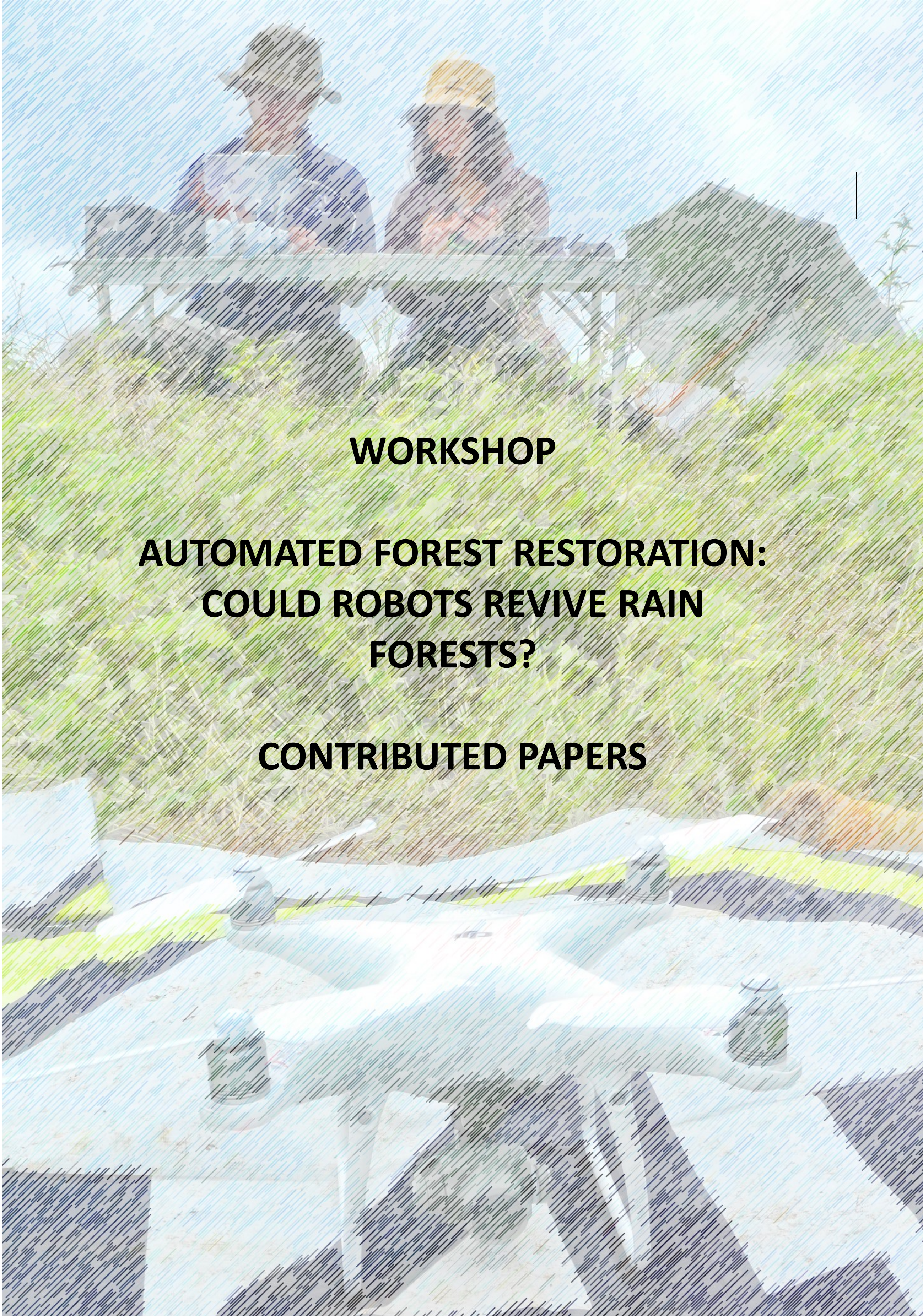

WORKSHOP

AUTOMATED FOREST RESTORATION: COULD ROBOTS REVIVE RAIN FORESTS?

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

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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

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

"consistent with the conservation of natural forests 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 restorations 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 available[7] (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

[10] http://ecosynth.org/

communities. They suggested that the use of small drones can help tropical 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 them[12].

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

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

[12] wadi.io/?page_id=90

different microphones, it is possible to triangulate the positions of the birds and 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

[13] http://skysense.co/

sites. After seeding, weed-control drones then continue to detect weed growth across the site and spray herbicides where and when necessary.

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

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

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 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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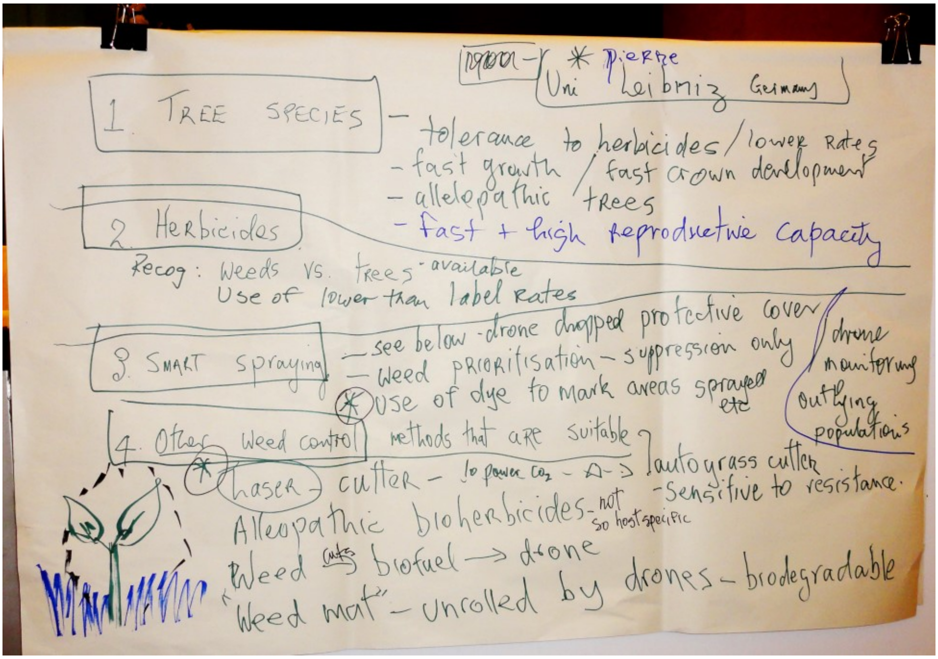

Figure 1.4 - Of all the discussion groups in the workshop, the debate on how to automate weeding probably generated the most innovative ideas.

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