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The potential for automating assisted natural regeneration of tropical forest ecosystems

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ABSTRACT

Assisted (or accelerated) natural regeneration (ANR) will play an important role in meeting the UN target to restore forest to 350 million hectares of degraded land, by 2030. However, since most accessible land is already used for agriculture, most of the sites, available for ANR, are far from roads and/or on difficult terrain, where implementing ANR with human labour is not practical. Therefore, this paper explores the potential of emerging technologies, such as low-cost UAVs (drones) and new imaging devices, to automate ANR tasks, including site monitoring (to assess site potential for natural regeneration, plan interventions and assess progress), maintenance of natural regeneration (particularly weeding) and species enrichment through aerial seeding. The usefulness of existing technologies is reviewed and future innovations needed, to provide practicable support for ANR, are discussed. Intensive collaboration, among technologists and forest ecologists, will be essential to ensure that technological innovations are based firmly on sound restoration science.

Abstract in Thai is available with online material.

Key words: aerial seeding; ANR; assisted natural regeneration; drones; forest restoration; hyperspectral imaging; imaging technologies; lidar; weed control.

Concern over global climate change and the growing interest in the role that forests could play in its mitigation have transformed tropical forest restoration from the wishful thinking of a few ecologists, 30 yr ago, into the global necessity it has become today. This has been encouraged by the expansion of REDD+ (Reducing Emissions from Deforestation and Forest Degradation) to cover 'enhancement of carbon stocks', including reforestation projects (United Nations 2007), with safeguards to ensure that local communities are fully engaged and biodiversity is conserved. Monoculture plantations cannot meet such safeguards, so REDD+ projects must adopt an ecological restoration approach (*acc.* Lamb 2015), to direct and accelerate ecological succession towards indigenous target forest ecosystems of the maximum biomass (*i.e.,* maximum carbon storage), structural complexity, biodiversity and ecological functioning that are self-sustainable within prevailing climatic and soil limitations (adapted from Elliott *et al.* 2013).

In 2014, the UN gave more impetus to the need to scale up forest restoration, when it announced the New York Declaration on Forests, which aims to restore forest to 350 million hectares of degraded land by 2030 (an area larger than India) to tackle climate change (United Nations 2014). The achievement of such an ambitious goal, however, may be limited by the inaccessibility of sites that are available for forest restoration. Most flat sites close to roads are already occupied with agriculture, leaving only less accessible areas available for forest restoration. Restoration projects in the tropics typically involve tree-planting; that is, first growing saplings in nurseries (which is expensive), and then using large numbers of people to carry baskets of saplings, equipment and materials on foot, often over long distances across steep or rugged terrain. Weeds are slashed with machetes and planting holes dug with hoes. Clearly, such an approach is not practical on sites more than a few hundred metres from vehicular access.

On less accessible sites, simply allowing forest succession to proceed naturally might be more feasible (Chazdon 2014, Chazdon & Guariguata 2016). In many areas, however, natural forest regeneration is inhibited by several factors, including: (1) fire, (2) herbaceous weeds (often invasive, exotic species) that compete with tree seedlings for light and soil resources, (3) livestock browsing and/or (4) the lack of a dense enough seed rain of desired tree species. Under such circumstances, 'assisted (or accelerated) natural regeneration' (ANR) becomes appropriate (Shono *et al.* 2007, Chazdon & Uriarte 2016). This involves implementing fire prevention measures, removing livestock, cutting or lodging weeds and/or erecting bird perches to increase the seed rain (Scott *et al.* 2000). A lack of seed sources could also be addressed by direct seeding (Doust *et al.* 2008, Bonilla-Moheno & Holl 2010, Tunjai & Elliott 2012) or by tree-planting, to increase the density of regenerants (*i.e.,* seedlings, saplings, trees and live tree stumps, capable of coppicing (Elliott *et al.* 2013)) to that required to close canopy within a desired period (usually a 2–3 yr project budget cycle) and increase species richness of the regenerating forest (Table 1).

Recent advances in technologies, such as UAVs (or drones) and imaging systems, raise the possibility of automating several of these restoration tasks. Drones provide easy access to remote sites. Compared with conventional aircraft, they are also cheap to

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buy and run, can be piloted with less training and can fly close to or even beneath vegetation canopies, without endangering a pilot. Various recently-developed imaging systems, which can be mounted on drones, could enable identification of restoration sites, where simple protection or ANR would be sufficient to achieve the desired restoration objectives and monitor progress (Zahawi *et al.* 2015). Such systems might also be capable of distinguishing between herbaceous weeds and trees (for weed control) and soon able to identify plant species (Baldeck *et al.* 2015). Aerial seeding by drones could complement ANR, where regenerant density falls below desired levels. Therefore, broadly speaking, such technologies might provide the 'A' in ANR in three main ways: (1) site assessment and monitoring, (2) tree maintenance, and (3) enrichment planting.

SITE ASSESSMENT AND MONITORING

Baseline site assessments are needed to: (1) determine the extent of existing natural regeneration; and (2) identify barriers to its progression (Brancalion *et al.* 2016). Such information forms the basis of restoration plans. Baseline surveys are typically carried out using circular sample plots (usually 5 m radius), positioned randomly across restoration sites. Within each plot, surveyors record the number and species of natural regenerants and, where necessary, calculate the number and species of complementary trees that may have to be planted, to achieve canopy closure within a desirable period. They also record barriers to regeneration, such as signs of fire, livestock browsing and soil degradation, to determine site management requirements (Elliott *et al.* 2013 Chapter 3).

Drone-mounted cameras and other scanning devices have the potential to collect such data more quickly and cost-effectively than conventional field methods and in far greater detail than that achievable from satellite imagery. Controlled by GPS, drones can fly rapidly and directly to pre-determined sampling points and record images, which can subsequently be analysed, either by eye or by computer algorithms, to determine the density of natural regenerants and signs of barriers to regeneration. Such procedures are becoming almost routine in agricultural systems (bestdroneforthejob.com/drones-for-work/agriculture-drone-buyers-guide/#The_Top_3_Agriculture_Drones_Ready_To_Fly), but on deforested sites, the main limitation of using conventional photography from drones would be detecting small regenerants, overtopped by herbaceous weeds. However, with laser scanning technologies rapidly advancing and becoming drone-based (Chisholm *et al.* 2013), it might soon be possible to 'see through' the weed canopy and even to identify the species of woody natural regenerants beneath (Maltamo *et al.* 2014).

The key measurable milestones, of tropical forest restoration are: (1) canopy closure or 'site recapture' (when the forest canopy closes and starts to shade out herbaceous weeds); (2) development of forest structure (multiple canopy layers, with an understorey of tree seedlings and saplings, indicating ecosystem self-sustainability); and (3) recovery of biodiversity levels and key species that are characteristic of the target (or reference) ecosystem.

Canopy closure is already easily detectable with drone-mounted cameras, whilst the development of forest structure could be assessed using drone-mounted lidar. Lidar involves firing a laser beam at an object and measuring the time taken for the laser light to be scattered back to a sensor. The time interval indicates the distance of the object from the apparatus. Flying a lidar unit over a forest results in a cloud of points that reveal the forest's three-dimensional structure. Such technology has already been used to monitor carbon stocks at the landscape level (Asner *et al.* 2010); an essential activity if restoration projects are to be funded under REDD+.

Similar results can now also be obtained with an image processing technology called 'Ecosynth' (ecosynth.org/), which uses large sets of overlapping digital photographs (taken with drone-mounted cameras), which are then processed with 'structure-from-motion' algorithms, to create 3D 'point clouds'. The point clouds can then be used to estimate the height, structure and roughness of forest canopies. Using such a system, with an inexpensive UAV and consumer-grade digital cameras over a 7–9-yr restoration site in southern Costa Rica., Zahawi *et al.* (2015) achieved high-resolution canopy structure measurements, comparable to those from field-based measurements Resolution of individual trees was easily achieved. The precision of the measurements was similar to those of a lidar-based remote sensing system. Unlike lidar, however, Ecosysnth does not require the use of lasers and special sensors, which are very expensive. The system uses ordinary digital cameras and open-source software and is much cheaper than lidar and may, therefore, be more practical.

One of the disadvantages of airborne 3D mapping, using digital photography, is its limited ability to identify points below the upper canopy layers. Below-canopy monitoring of ANR sites will be necessary for assessments of biomass and carbon storage. A recent study by Chisholm *et al.* (2013) showed how this might be achieved by using a remotely-piloted, battery-powered UAV, mounted with a miniaturized lidar unit, flying beneath tree crowns in a Singapore woodland and post-processing software, which they developed themselves. The system could measure diameters at breast height (dbh) of 73 percent of the larger trees (dbh>20 cm), within 3 m of the flight path. Lidar measurements correlated well with conventional measurements (median absolute error 18.1%). Although the resolution of small, drone-mounted lidar units is currently lower than that of airplane-borne systems, drones can get much closer to the trees being scanned and can therefore generate very high resolution datasets (Wallace *et al.* 2012).

Monitoring recovery of plant species diversity in ANR sites, with drone-mounted imaging systems, may also be possible. The main technology, currently being developed to do this, is imaging spectroscopy (or hyperspectral remote sensing), which measures light (visible and infrared), reflected from forest canopies, in hundreds of narrow, mostly contiguous spectral bands. 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 indicate its species. Unfortunately, spectral signatures vary considerably among trees within species, due to tree age and health, slope, attitude, phenology, and time of day etc. Consequently, identification of *all* tree species in tropical forest canopies may require considerable further research and development. However, in a recent paper, Baldeck *et al.* (2015) were able to recognize the crowns of three target species with an accuracy of 94–100 percent, against a background of 'everything else', using 167 bands of spectral data, analysed with a biased support vector machine. Hyperspectral imagery can also be combined with airborne lidar data, which delineates tree crowns and performs orthorectification (removing the effects of image tilt and terrain). Furthermore, lidar can add new variables to the data set, such as tree height, crown dimensions and surface texture, which may contribute towards species identification (Latif *et al.* 2014, Singh *et al.* 2015).

With a little more development, the systems summarized above could also be used to determine if a sufficient diversity of tree seed sources exist within remnant forest patches situated within seed-dispersal distances of restoration sites. The incoming seed rain can greatly affect tree density, time-to-canopy closure, species richness and species composition of natural regeneration (Angel *et al.* 2006, Blackham *et al.* 2013, Caughlin *et al.* in press), so surveys of nearby seed sources would be useful in determining where ANR might be successful. Automated mapping of seed trees could also be used to increase the efficiency of seed collection, where ANR needs to be complemented with direct or aerial seeding. This task might also be possible, using the emerging plant species identification tools, based on matching images of flowers or fruits etc. with a database of known images. Such technologies are already being used with smart phone apps to identify plant species (*e.g.,* Pl@ntNet (m.plantnet-project.org/) and Leafsnap (leafsnap.com/) and could easily be transferred to drone-mounted cameras. However, for such systems to be useful, the image databases would have to be expanded, to include the tropical tree species that occur in and around each ANR site, and the reliability of the underlying algorithms improved.

The ultimate indicator of forest restoration success is the return of breeding populations of animal species, typical of the target (or reference) forest (Omeja *et al.* 2016). Digital photography from drones has already 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 from above. Therefore, thermal imagery, which is capable of detecting animals beneath the forest canopy, is now being developed to detect and identify animals (Christiansen *et al.* 2014).

At ground level, digital camera traps have been used for many years to capture wildlife images. However, retrieving data from camera traps and replacing their batteries in remote sites is 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 researchers retrieve the cameras (*e.g.,* www.reconyx.com/product/PC900C-Cellular-HyperFire-Professional-Covert-IR).

Outside the range of cellular telephone networks, researchers can now retrieve images from camera traps by using drones as 'data mules'. For example, the Wadi Drone, developed by four New York University Abu Dhabi students, Martin Slosarik, Ting-Che Lin, Vasily Rudchenko, Kai-Erik Jensen, is a fixed-wing drone with a 2.5 m wingspan. It automatically retrieves images from cameras, via Wi-Fi, when it flies within 300 m of them (wadi.io/?page_id=90).

Birds are harder to see but easier to hear and bats are also more readily detected and species identified from their ultrasound echolocation calls. So remote auto-surveys of birds and bats might be possible by placing arrays of microphones (autonomous recording units or ARUs) 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, create a dynamic map of bird territories across the restoration site and derive population density estimates (Lucas *et al.* 2015).

TREE MAINTENANCE

Competition with herbaceous weeds is the most common reason why relying on natural regeneration alone fails to achieve restoration goals. Therefore, weeding is the most common ANR maintenance treatment. It can include ring-weeding (hand pulling or digging weeds out by their roots, within 50 cm of regenerants), lodging (flattening weeds between the exposed natural regenerants with wooden boards) or herbicide application. All these tasks require large amounts of human labour and easy access to the sites. In the tropics, weeding must be repeated every 4–6 wk during the rainy season, if it is to have any significant effect (Elliott *et al.* 2013 Chapter 5). It is demanding work, and field workers are unlikely to do it if they are not closely supervised. It is also the most expensive ANR task, so automating it would considerably reduce the costs of restoring less accessible site. However, it is also by far the most difficult of all ANR tasks to automate. Since precise mechanical weed removal is unlikely to become feasible using drone-based tools, herbicide spraying will probably become the preferred method used to develop auto-weeding systems (Fig. 1).

Glyphosate is currently the most widely used herbicide in forest restoration. A systemic, non-residual herbicide, it is highly cost-effective. 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 percent 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, use of glyphosate near natural regenerants is problematic, since the spray can drift onto tree foliage and kill the trees (Torezan & Mantoani 2013). Therefore, achievement of auto-weeding technologies will probably depend on the use of existing herbicides that are more specific or the development of new ones. Herbicides are classified as grass-

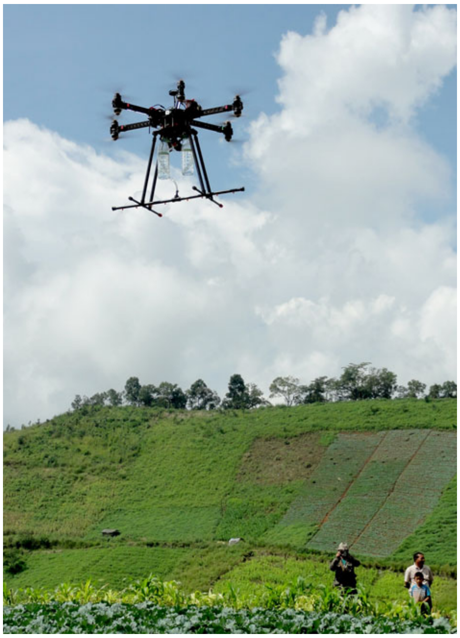

FIGURE 1. Drones, capable of spraying herbicides (and other liquid pesticides), whilst remaining stable, are already being used in agriculture. This one, which carries 2 Litres, was developed by Bird's Eye View (BEV), Chiang Mai. For AFR, such spraying ability must be matched with AI to direct herbicides onto weeds, without spraying tree seedlings and saplings.

specific (graminicides), broadleaf-specific (kill or inhibit herbs and tree seedlings but not grasses) or non-specific (kill or inhibit most green plants). Graminicides are already used in forestry (Clay *et al.* 2006).

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. Therefore, the possibility exists that highly selective herbicides could be developed for ANR. One avenue of research that might yield results, is the development of 'bio-herbicides' exploiting the allelochemicals, naturally produced by some herbaceous weed species to inhibit seed germination of other weed species (Cheng & Cheng 2015). What is ultimately needed is 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 chemicals exist, but it may be possible to develop some, by identifying and exploiting key biochemical differences between woody and non-woody plants, although this will most likely take many years of research and testing.

A second element in the achievement of auto-weeding systems might be 'smart spraying'—development of more accurate and 'intelligent' spraying technologies. Smart spraying would involve combining drone-based spraying devices with plant recognition systems, capable of distinguishing between herbaceous weeds and natural regenerants. Drones would then deliver herbicide onto the weeds, but not the regenerants. 'Machine vision' systems for detecting weeds amongst crops emerged in the 1990's, (Thorp & Tian 2004) and have advanced considerably since then. More recently, Thomas Wilder and Cynthia Johnson demonstrated a potentially drone-based weed-control system, using a HANA database to identify weeds via an infrared sensor. The system dispensed one of four different herbicides directly onto each weed, based on weed species and size (events.sap.com/teched/en/session/13694). Drone-based weed recognition could perhaps be developed from the plant-recognition systems, referenced above (*i.e.,* Pl@ntNet and Leafsnap). Such systems attempt to identify plants to species level, but in fact, a drone-based weed-detection system for ANR would not need this level of precision. It would only be necessary to distinguish 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 also be needed, but this is still a much simpler computational process than identifying individual plant species.

The greatest challenge to developing auto-weeding technologies for forestry will be designing drones capable of operating close 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.

ENRICHMENT PLANTING

Where the density natural regenerants is too sparse to achieve canopy closure within the desired period, enrichment planting to increase both regenerant density and species richness becomes necessary. In most projects, this is achieved by tree planting, but direct seeding has also been used (Doust *et al.* 2008, Bonilla-Moheno & Holl 2010). Since containerized tree saplings are heavy and bulky, transporting them to remote sites is expensive and arduous. They are also difficult to plant robotically. Therefore, aerial seeding will most likely become the most practical method of boosting ANR, where regenerant density falls below the minimum required.

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 they require both an airport and a pilot, with years of training, for their operation. Drones provide a cheaper, more practical and more precise method of targeted aerial seeding into deforested sites and are already being developed for this task (Fig. 2).

UK company, BioCarbon Engineering, has developed a drone that uses compressed air to propel seeds in small biodegradable plastic pods, containing a nutrient gel, into the soil from 2–3 m above the ground. The gel protects the seeds from the impact and helps them to stick to the soil. When fully developed, each drone will be able to deliver up to 12,000 seeds per day, with up to six drones controlled by each operator (www.biocarbonengineering.com/).

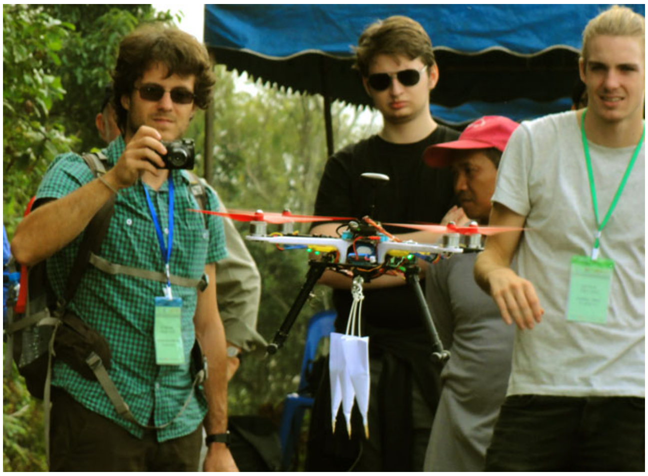

FIGURE 2. Seed bombs can be as simple as paper cones, containing seeds in forest soil, mixed with polymer gel. The drone, pictured here was made by Chiang Mai University Physics Department and releases the bombs using a simple rotating spiral (from the 1st Workshop on Automated Forest Restoration, Chiang Mai University, October 2014).

In ecological terms, we may think of such drones as carrying out the same dispersal function as frugivorous animals (excluding fruit pulp removal and seed processing within digestive tracts), but doing so at a vastly accelerated rate. Over much of the tropics, the larger animals, which formerly dispersed tree seeds from forests into deforested areas, have been extirpated (*e.g.,* elephants, rhinos, wild cattle, hornbills, and large fruit bats, etc.). Consequently, artificially replacing their ecological, seed-dispersal function with drones may be a critical stopgap measure, until such seed-dispersing animals can be re-introduced.

The main areas of research, required to advance aerial seeding by drones are: (1) seed technologies; (2) techniques to increase seed supply; and (3) precision auto-weeding.

The possibility of carrying out aerial seeding, with drones dropping seed 'bombs' (seeds within rapidly degradable projectiles) or pellets (seeds with an artificial seed coating) presents many opportunities, in terms of providing seeds and young seedlings with performance-enhancing resources that are not naturally provided by either fruits or seed-dispersing animals. Gels within seed bombs, or materials used for seed-pelleting, could contain nutrients, chemicals to deter seed predators, symbiotic microbes, anti-stress chemicals and much more. For example, predator repellents have been tested for conventional aerial seeding in forestry since the 1990s (Nuyun & Jingchun 1995) and aspirin, applied as a seed coating, has already proved effective at reducing drought stress in vegetation restoration in arid environments (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).

With drones capable of delivering vast numbers of seeds per day, seed supply becomes a critical factor. It is already an issue, even for the production of native forest tree planting stock in nurseries (Bozzano *et al.* 2014). Automated detection of seed trees, already discussed above, is therefore likely to become an important component of assisted restoration.

Finally, auto-weeding, on the very fine scale required to remove competition from around small, recently germinated seedlings, is perhaps the greatest challenge. Although it is conceivable that the smart spraying systems, mentioned above, could be developed for relatively large regenerants (>50 cm tall), it is difficult to envisage a system with enough precision to spray herbicides on weeds, without also spraying small tree seedlings, just emerging from aerial seeding. Therefore, the development of highly specific herbicides is likely to become a critical area for research for the ultimate success of aerial seeding. A summary of all the above-mentioned automated techniques and their pros and cons, relative to standard manual practices, is presented in Table 1.

FUTURE PROSPECTS

If forest restoration is to be implemented at the scales envisioned by the UN, it seems that some degree of automation of the more laborious restoration tasks would be beneficial. Ten years ago, most of the technologies, described above, were science fiction; but not any longer. Although several of them have become almost commonplace, most would require considerable advancement, before they could provide practical assistance to forest regeneration. Therefore, The next research and development challenges are to improve these technologies and integrate them in innovative ways to tackle restoration tasks cost-effectively.

Many obstacles remain. Drones are still at an early stage of development. Short battery life (usually much less than 1 h) currently limits their usefulness for auto-restoration tasks. Fortunately, battery technologies are advancing rapidly, hydrogen fuel cells have now extended the flight times of drones to several hours (www.bbc.com/news/technology-35890486), so we may not have to wait too long before long-distance drone flights will become routine. However, for true automation of forest restoration tasks, drones will have to be able to recharge themselves and several technologies are now available for that. The most advanced is electromagnet induction pads (Jung *et al.* 2012), similar to those used to charge mobile phones. Under field conditions, charging pads could be powered by solar-charged batteries, requiring very little human intervention.

Enabling drones to fly under forest canopies and over weed canopies by autopilot will require advanced object-avoidance technologies, probably beyond those available today, since vegetation presents insubstantial obstacles (twigs and leaves), which are continuously moving. However, guidance and object-avoidance technologies, currently being developed for urban search-and-rescue drones, may well enable drones to fly autonomously under the canopies of forests in the near future (www.dronesforgood.ae/finals/highly-maneuverable-usar-robot). Even off-the-shelf drones are now being sold, bundled with rudimentary object-avoidance technology.

As with all new technologies, costs are initially high, although they are rapidly declining. For example, early, mass-produced

TABLE 1. *Manual and automated ANR methods compared*

	Manual		Automated		
General	Slow. Labour intensive. Expensive. Only suitable for sites near roads. High transportation costs. Can be implemented now, with simple skill sets and minimal training. No need for research and development.		Rapid. Development costs high, but running costs low. Enables restoration on inaccessible sites. Lower transportation costs. Requires highly skilled researchers to develop mechanisms, but could be implemented with simple skill sets. Research required to improve existing technologies, develop new ones and reduce costs.		
Task by task	Methods	Pros and Cons	Methods	Pros and Cons	Research and Development Needed
Pre-restoration site assessment	Field team samples vegetation, counts regenerants, estimates weed cover, records barriers to regeneration.	Small sample plots cover low percentage of the site. Eyes at ground level more likely to detect small or obscured regenerants.	Digital photography by drone. Interpretation by eye or computer algorithms.	Covers a wide area in a short time. Small or obscured regenerants less likely to be detected from above.	Development of more efficient algorithms, particularly to separate small tree crowns from weed canopy.
Weeding	Slashing with blades. Digging out roots with hoes. Manual application of herbicides.	Health hazards. Often, lack of available local labour.	Smart herbicides and/or smart spraying by drones, combined with plant recognition systems.	Unlikely to completely avoid spraying smaller regenerants among weeds.	More accurate and real-time plant recognition technologies. Highly directed spraying systems. Development of smart herbicides will take many years.
Locating seed trees	Walking along trails, scanning underside of forest canopy with binoculars for fruiting trees.	Scans very small area. Seeds tend to be collected from a few well-known trees. Narrows genetic diversity during seed collection.	Recognition of fruiting trees from above, by imagery from drones. Seeds collected by drone-mounted tools.	Imagery systems already at prototype stage. Only small batches of seeds could be collected per drone flight.	Improvement of imaging systems to recognize tree crowns with ripe fruits. Build databases of tree chracteristics, used to identify species from drone-mounted imaging devices. Drone-mounted seed collection tools not yet developed. Object-avoidance technologies must be improved, to enable drones to operate near or within tree crowns.
Enrichment planting	Conventional tree planting. Hauling trees, materials and equipment onto restoration sites in baskets on foot.	Practical only on sites accessible by vehicles. Lack of local labour. Survival of tree saplings higher than that of trees grown from seed.	Aerial seeding by drone	Drone and seed delivery technologies already at prototype stage. Trees, growing from seed, are more vulnerable to weed competition, compared with planted saplings.	Seed enablement technologies to increase germination and early seedling establishment.

(continued)

TABLE 1. *(continued)*

Task by task	Methods	Pros and Cons	Methods	Pros and Cons	Research and Development Needed
Monitoring					
Canopy closure	Hemispherical photography from the ground.	Expensive equipment, must be moved manually from point to point.	Digital photography by drone from above canopy. Interpretation by eye or computer algorithms.	Covers a wide area in a short time.	Development of more efficient algorithms to separate small tree crowns from weed canopy.
Forest structure and carbon	Measurements of basal area with tape measures. Allometry.	Allometric equations to estimate carbon storage have high error margins.	Drone-mounted lidar below canopy to measure tree dimaters.	Technology already at prototype stage.	Improve accuracy of algorithms to convert tree diameters into biomass.
Tree species richness/diversity	Ground survey.	Sample plots usually cover a small proportion of the area. Needs qualified botanist in the field or shipping of specimens to an herbarium.	Digital photograph by drone with pattern-matching algorithms to identify species.	Technologies already working (e.g. Pl@ntNet). Drones can cover wider areas, more rapidly, than on-the-ground sampling.	Enlarge data-bases of tree images for pattern-matching.
Wildlife recovery	Direct observation or recording tracks and signs.	Small animals more likely to be recorded. High transportation costs. Researchers disturb wildlife. Health and safety hazards of field work.	Advanced camera traps and microphone arrays. Data transfer by phone network or drone “data-mules”. Thermal imagery from drones.	Expensive equipment. But lower transportation costs and lower health/safety risks. Less disturbance to wildlife.	Delivery and pick-up of camera traps and microphones by drone (?)

drones cost several thousand dollars, but now their price has fallen to a few hundred dollars and simple radio-controlled models, capable of carrying out basic visual surveys, can be bought for as little as 50 US$. Drones, capable of carrying the payloads described above can already be purchased for 1000–5000 US$ and are likely to become even more affordable in the near future. Furthermore, open-source hardware and software for drones are growing in popularity, such as the Flone movement, with drone frames made of wood (so they biodegrade if lost) (Fig. 3) and controlled by free smart phone apps (play.google.com/store/apps/details?id=processing.test.floneremote&hl=en). Such systems are becoming popular for increasing involvement of communities in environmental issues. Nevertheless, the costs of all the technologies described above, particularly the imaging technologies, still have a long way to fall before automated ANR becomes an attractive proposition to sponsors and investors.

The realization of automated ANR will require intensive collaboration among ecologists and technologists, with widely diverse backgrounds and fields of interest. It is essential that sound restoration science drives the technological developments and not that technological advancements result in the sacrifice of restoration principles. It would be a disaster if, for example, rapid-firing, seed-dropping drones were to be used to establish regimented mono-species plantations of exotic economic trees across sites, which could have been used for ANR. Therefore, Cross-disciplinary collaboration must be encouraged, to develop automated restoration technologies that are cost-effective, socially acceptable and above all, scientifically sound.

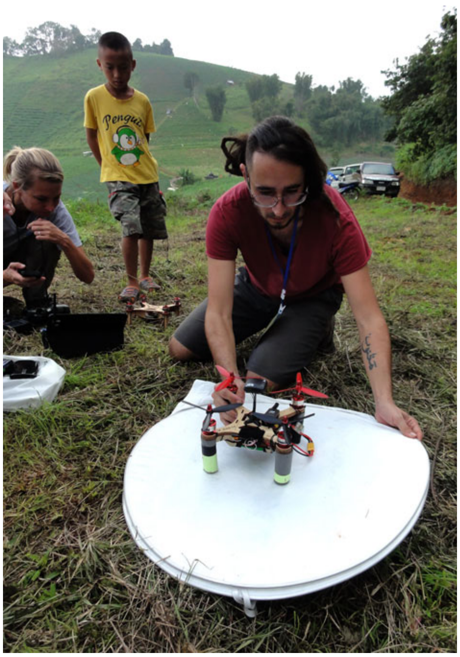

FIGURE 3. Flones are low-cost, self-assembled drone kits, with biodegradable wooden frames, controlled by free, open-source, smart phone apps. They are perhaps the easiest way to involve local communities in simple forest restoration tasks, such as monitoring progress with digital photography.

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