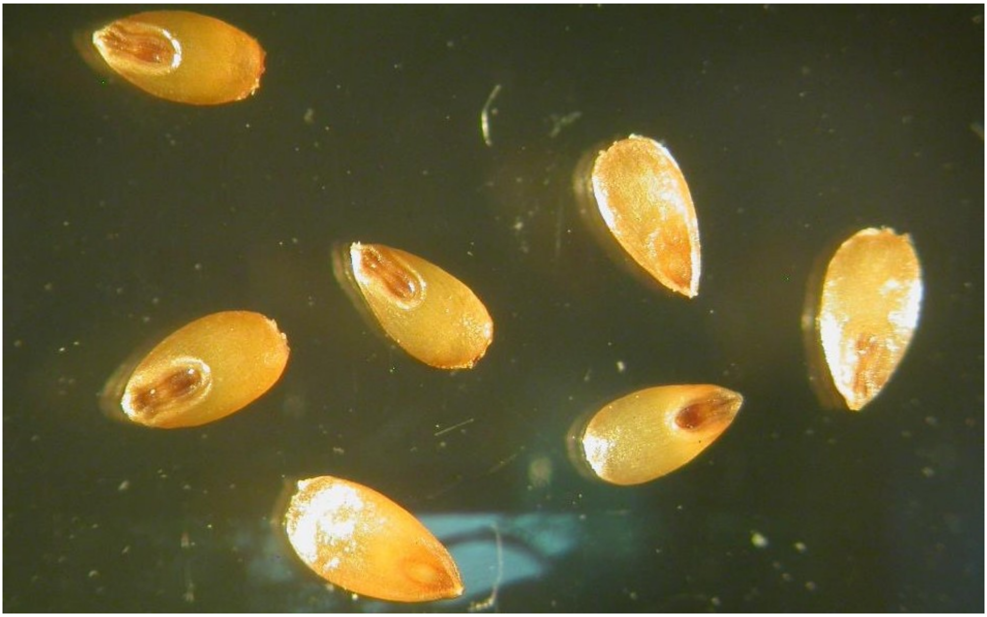

Figure 9.1 - Australian grass seed which are the subject of significant seed-enablement research

Figure 9.2 - Uncoated, coated and pelleted seed

Chapter 8

SMART SEED FOR AUTOMATED FOREST RESTORATION

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ABSTRACT

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

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

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

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INTRODUCTION

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

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

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

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

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

AERIAL SEEDING

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

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

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

Species selection

Non-native species have often been used for aerial seeding, usually because their seeds are cheaper and easier to obtain than those of native species. In some cases, introduced species have been replaced by natives (GREIPSSON & EL-MAYAS, 1999), but usually competition negatively affects native species re-establishment. In the past, very little attention was given to the selection of species and the origin of the plant material. Post-WWII aerial reforestation of Pacific Islands was done mainly with the legume *Leucaena leucocephala*, non-native to all of the islands where it was sown (it comes from S. America). It was considered a very promising plant with potential economic interest (NATIONAL ACADEMY OF SCIENCES (U.S.), 1977) but, it rapidly became invasive, covering most of the available area, severely disrupting indigenous vegetation and threatening the survival of many rare, endemic plant species (PACIFIC ISLAND ECOSYSTEMS AT RISK, 1999). The IUCN lists it among top 100 "world's worst invasive alien species". Focusing solely on functional outcomes and short-term economic gain can thus have serious negative consequences on long-term ecosystem health and ecological trajectory that may be costly to correct. Therefore, it is crucial that local indigenous species are employed to the greatest possible extent, to avoid such problem (SOCIETY FOR ECOLOGICAL RESTORATION INTERNATIONAL SCIENCE & POLICY WORKING GROUP, 2004).

Soil

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

Seedlings and seed bombs

To overcome the problems of on-site germination, seedlings, contained within aerodynamic projectiles, have been dropped from aircraft (JOHN WALTERS, 1972). Some of these seedling containers for aerial delivery have been patented (AGNAGOSTOU, 1966; WALTER & GARTHSORE, 1973; ARNOLD, 1982; GORDON, 1982) but, the logistics required to protect growing seedlings adds complexity to the already-challenging process of aerial delivery. Therefore, aerial reforestation using only seeds is much more common (WOOD, 2000).

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

Dart for drones

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

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

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

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

Equipment and seeding rate

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

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

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

UAV seeding equipment

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

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

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

SEED-ENABLEMENT TECHNOLOGIES (SET)

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

Seed priming

Priming involves subjecting seeds to pre-sowing controlled hydration (Fig 9.1), sufficient to permit pre-emergence metabolic activity but insufficient to allow radicle emergence, followed by re-drying for ease of handling and sowing (KHAN, 1992). Seed priming promotes more rapid and synchronous seed germination of many horticultural and agricultural species (BROCKLEHURST & DEARMAN, 1983; BRADFORD, 1986; KHAN, 1992; HARRIS et al., 2001). Whilst published studies on the effects of priming on germination of wild species, are limited, such techniques are well established in agricultural and horticultural enterprises and clearly provide promise for the restoration industry and could be beneficial with little additional weight or bulking problems for drone-based delivery systems.

Seed Coatings

Seed coating consists of creating an artificial external coat around single or agglomerated seeds using polymers, inert powders and active compounds. It improves seed handling through physical modification (Fig. 9.2) and protects seeds from predation and diseases by delivering specific treatments. These techniques are effective in reducing rodent and bird predation of crop seeds and limit the effects of seed-borne diseases and fungi (SCOTT, 1989).

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

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

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

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

The seed coating industry and research

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

Coating nomenclature

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

A seed is considered coated when its surface is covered by coating agents and its weight gain is usually less than 20%. For greater weight increases, treatments are classified as encrusting, as long as the original shape of the seed remains. Once the shape becomes spherical, the seed is considered pelleted. Seed coating and encrusting are on a weight gain basis, whereas pellets are measured by diameter increments (Fig 9.2).

Seed-coating equipment

The equipment employed closely resembles that used for coating in the pharmaceutical and food industries. The first seed coating machines were rotating pans based on a model originally patented in the 19th century (WILLIAM E. UPJOHN 1885) for making medicinal pills. Since then, more than 20 patents on seed coating machines have been lodged but, according to GREGG & BILLUPS (2010), the most widely used machines today, along with the rotating pan, are based on rotor-stator (Fig 9.3) and fluidized bed technologies. For projects with low budgets and limited access to these technologies, affordable alternatives have been described in although compound delivery precision, coat/pellet quality and large-scale replicability could be limited. The most commonly employed alternative equipment are cement mixers (HATHCOCK et al., 1984; HODGSON & MCGHEE, 1992), bags that are shaken with seeds (AVELAR et al., 2012) and manual application of materials onto seeds (CORLETT et al., 2014).

Seed-coating materials

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

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

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

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

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

Coatings for AFR

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

Biochar and mycorrhiza coatings

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

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

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

Seed coatings for restoration

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

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

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

CONCLUSIONS

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

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Figure 9.3 – Seed-coating equipment, lab-scale rotary coater on the left, rotating pan on the right.

Figure 9.4 – *Acacia* seed balls, made with biochar, in Kenya