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

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

Figure 5.3 - Saplings, 18 months after direct seeding.

Chapter 5

DEVELOPING AERIAL SEEDING BY UAVS: LESSONS FROM DIRECT SEEDING

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

ABSTRACT

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

INTRODUCTION

As a tool for forest restoration, direct seeding means sowing the seeds of forest tree species directly into the substrate of restoration sites, usually by hand. The technique is cheaper than conventional tree planting, since no tree nursery is needed to produce the planting stock (TUNJAI & ELLIOTT, 2012), but it also has several disadvantages, particularly in the tropics.

Firstly, seed predation in open deforested sites can be very high (HAU, 1997). Secondly, germination rates can be very low, due to desiccation in exposed sites and the mortality rates of seedlings, growing from seeds in the field, is usually much

[1] Forest Restoration Research Unit (FORRU), Biology Department, Faculty of Science, Chiang Mai University, THAILAND 50200 (p.dia.shannon@gmail.com)

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

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

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

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

FACTORS AFFECTING THE SUCCESS OF DIRECT SEEEDING

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

Site and species selection

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

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

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

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

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

Seed supply and quality

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

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

Site preparation

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

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

Sowing methods

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

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

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

Post-sowing management

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

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

FURTHER RESEARCH

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

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

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