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OPINION ARTICLE

Forest restoration is more than firing seeds from a drone

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We are witnessing a rapid increase in news sending the message that drone seeding is a promising technological solution to implement forest restoration at large spatial scales. However, there are neither reports regarding success nor peer-reviewed studies to support these assertions. Once in the ground, the seeds and the seedlings and saplings that they generate have to face biotic and abiotic hazards that can strongly reduce regeneration potential. Successful forest restoration, therefore, cannot be achieved by simply dropping seeds from the air. We summarize some aspects to take into account before considering drone seeding as an efficient and widely applicable technology for forest restoration. A first step should be to increase the precision of drone seeding—contrary to the current massive firing of seeds—in order to concentrate the efforts in the best microsites for establishment and reduce the number of seeds needed and the cost of the whole operation.

Key words: aerial unmanned vehicles, drone seeding, forest restoration success, seed broadcasting, seedling establishment

Conceptual Implications

- Aerial seeding using drones is being widely proposed by private companies and media as a promising and cost-effective solution for ecosystem restoration. However, peer-reviewed data on the success of these initiatives is still needed before relying on this technique.
- If we are to consider drone seeding to be a widely applicable technology, further research and experimentation relating to plant performance once the seeds are in the field is necessary to ensure restoration success.
- Instead of mass seed firing, a greater precision approach should be used when seeding with drones to deliver the seeds to specific sites, even at a submeter scale. It is most likely that recruitment will occur under appropriate safe sites, thereby reducing seeding rates, costs, and maximizing success.

Introduction

We are witnessing unprecedented interest in restoring the world's forests (Mansourian et al. 2021). There are several reasons for this, possibly the most important being an increased social and public awareness of the role that nature and its ecosystems play in human well-being. This awareness and interest is being translated into policies at different scales that are generating impressive initiatives to restore ecosystems—forests in particular—in an attempt to mitigate the effects of climate change, biodiversity loss, local and regional impoverishment, and even pandemic risk (FAO 2020). Some global examples are the New York Declaration on Forests, the Bonn Challenge, and the UN Decade on Ecosystem Restoration, which all together seek to plant millions of hectares of forests (Fagan et al. 2020; Castro et al. 2021). Furthermore, there is an increasing (although controversial) trend of tree-planting projects within the framework of carbon credit markets (Hunt 2008; Philipson et al. 2020), which highlights how forest restoration will likely continue to grow. Altogether, this is creating a unique opportunity to upscale forest restoration endeavors at an extraordinary rate.

The task of restoring forests at such a large scale poses enormous challenges. Success is one of the key challenges: if we seek to restore the forest, we should try to guarantee that what we plant or seed today will become a forest in the medium- to long term. In addition, it poses an economic and operative challenge: how to achieve the restoration of millions of hectares at an affordable cost, considering also that in many cases the areas that can or should be restored are in remote and hard-to-access places (Mohan et al. 2021). In this context, aerial seeding with drones is being proposed as a smart, pragmatic solution by an

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Table 1. Summary of the major company websites with a main focus on large-scale drone seed sowing. The keywords "drones," "UAVs," "reforestation," "tree planting," "seeding," "aerial seeding," and "seed sowing" were combined in the Google search engine on 5 May 2022 to obtain the main results of large-scale drone seeding companies. Additionally, the results were contrasted and complemented with the work conducted by Mohan et al. (2021). Overall, these websites does not provide precise information on the substances used for pelleting or coating, seeds broadcasted per hectare, or peer-reviewed data on seedling establishment success. [a]General information about seed coating composition reported in Aghai & Manteuffel-Ross 2020; not a peer-reviewed journal. [b]General information about seed coating composition (only report the use of clay). [c]General information about seed coating composition ("root growth promoters, organic fertilizers, super-absorbent polymers, natural herbicides, and organic repellents"). [d]Data of success reported in Aghai & Manteuffel-Ross 2020; not a peer-reviewed journal).

Company	*URL*	*Country*	*Precise Information on Coating Substances Employed*	*Data of Success Reported*
Drone seed	https://droneseed.com/	United States	No[a]	Yes[d]
AirSeed	https://airseedtech.com/	Australia	No	No
Flash Forest	https://flashforest.ca/	Canada	No	No
Dronecoria	https://dronecoria.org/en/main/	Spain	No[b]	No
CO_2 Revolution	https://co2revolution.es/	Spain	No[c]	No
Dendra System	https://dendra.io/	UK	No	No
Lord of the Trees	https://lordofthetrees.ai/	Australia	No	No
Seedcopter	http://seedcopter.com	India	No	No
CAFU	https://www.cafu.com/the-ghaf-project	India	No	No
Distant Imagery	https://www.distantimagery.com/	United Arab Emirates	No	No

increasing number of companies and webpages (Table 1), and more and more news is appearing in the media around the world about the benefits of seeding with drones for forest restoration (Table S1). However, there are neither reports of the success of these initiatives (Mohan et al. 2021), nor peer-reviewed scientific studies that confirm if drone seeding may be efficient (Table 1,S1). As presented by the companies and the media, it seems that the objective is to develop a highly technological solution and that the use of the drones is an objective per se, rather than focusing on the rigorous analysis of the results in terms of restoration success. Whatever the method used, we must consider that once placed in the field, the seeds and the new individuals that they generate have to face biotic and abiotic hazards that can strongly reduce regeneration potential. Moreover, we have to make sure that the chosen restoration method does not harm the environment. Although seed sowing with drones may provide multiple advantages for forest restoration, we must make a critical and constructive assessment of the problems that remain to be solved before beginning to use it as a global technology. Here we summarize some aspects to take into account before considering drone seeding as an efficient and widely applicable technology for forest restoration.

Seed Predation and Consequences of Pelleting and Coating for Fauna

Postdispersal seed predators may greatly reduce the amount of seeds available for the following phases of recruitment across many life forms of plants, including trees (Holl & Lulow 1997; Hulme 1998; Wang et al. 2021). Consequently, broadcast seeding and aerial seeding campaigns can fail due to high rates of seed predation (Nelson et al. 1970; Shannon & Elliott 2020), particularly by birds and mammals. Coating and pelleting the seeds, which is commonly practiced today as part of aerial drone seeding (Table 1), might deter the activity of seed predators (Pearson et al. 2019). However, despite successful cases under laboratory conditions, there is still very little information about which substances really reduce seed predation in the field, or how to apply them to ensure that their protective effect lasts long enough (e.g. Pearson et al. 2019). For example, capsaicin has been used to deter seed predation by rodents. However, studies under field conditions show a reduced effect or no protective effect at all (Leverkus et al. 2013; Pearson et al. 2019), and even a negative effect on seedling emergence (Leverkus et al. 2013). In addition, we have an absolute lack of knowledge on the potential effect of the coating and pelleting substances used for aerial drone seeding on animal health were they to ingest those seeds. We know that coating substances used for crop seeds may affect negatively vertebrate health (Lopez-Antia et al. 2016; Poliserpi et al. 2021). The point raised by these studies is that we need to know the effect of the coating and pelleting substances for aerial drone seeding on the biota to decide if those treatments should be used or could be tolerable in case they had some effect. To date, no studies report data on the issue of the effects of seed coatings used for drone seeding on other organisms, nor is there a comprehensive dataset or approved standards for the substances used in such coatings. More research and oversight is clearly needed before these techniques can be responsibly scaled up.

Seedling Establishment and Sapling Performance

Once in the ground, the seeds that survive predation must germinate and the seedling must grow to the juvenile stage. During these phases of recruitment, the losses of demographic potential are enormous in plant species, a simple fact that can be generalized in all ecosystems and which has been studied extensively since the foundation of plant ecology (Harper 1977; Peet & Christensen 1987). Abiotic factors such as drought or frost, or biotic factors such as competition with other plants or herbivory by invertebrates and vertebrates, can substantially decrease seedling survival across biomes, even to the point of eliminating all the seedlings emerged in a particular year (Castro et al. 2004; Krauss et al. 2008; Van Nedervelde et al. 2015; Garcia et al. 2020). Subsequently, saplings may also suffer abiotic

(Herrero et al. 2013) and biotic stresses that reduce recruitment success. In particular, herbivory by wild and domestic large mammals, which are a common element in many ecosystems to be restored, is a main determinant of sapling mortality and retarded growth, and a major cause of reforestation failures (Darwin 1859; Savill et al. 1997; Takatsuki 2009). Current seed-enhancing technologies such as seed priming, coating, or pelleting may promote early seedling establishment, but their effect will fade with time and will scarcely provide protection against environmental stress through the sapling stage.

Seed Provisioning and Origin

The above-mentioned losses of regeneration potential can be compensated with a higher number of seeds. In fact, seed broadcasting (either by hand, from terrestrial vehicles, or by air) has been and it is widely used for reforestation (Novikov & Ersson 2019; Pedrini et al. 2020). The key issue is to adjust the density of seeds to an expected number of trees discounting mortality through plant recruitment. There are very few reports, however, about seedling recruitment after drone seeding (Mohan et al. 2021), so it is difficult to estimate a minimum density of seeds required. Furthermore, the drone seeding campaigns that are announced in the media rarely report the number of seeds dispersed per unit area (Table 1), an aspect that is essential to judge the usefulness of massive drone seeding. This raises the question of whether seed provisioning for aerial seeding is possible at the large restoration scale that is globally intended. Broadcast seeding use densities that usually are above 100,000 seeds per hectare (e.g. Burns & Honkala 1990; Boydak 2003; Novikov & Ersson 2019), which is very often above the values of seed production of native forests (e.g. Burns & Honkala 1990; Koski 1991). Moreover, we have to take into account processes such as seed masting, pre-dispersal seed predation, and technical and operational issues related to seed collection, which might considerably reduce the amount of seeds harvested. Seed enhancing technologies may increase the recruitment success per seed, therefore reducing the number needed, but this has yet to be tested or reported. Besides, most late-successional trees—which should be the main targets for restoration—produce large seeds and, thus, a lower number with respect to early-successional species (Castro et al. 2006), making it more difficult to provision seeds. All this implies that the required massive seed harvesting for seed firing with drones at large scales may deplete local seed stocks and entail the acquisition of seeds from distant locations. This may raise additional issues, as the threats to indigenous genetic diversity and loss of local adaptations (Bozzano et al. 2014).

Summary: Towards a More Precise Drone Seeding

In summary, aerial seeding with drones is a technology that might be tremendously helpful in forest restoration. However, to restore the forest is not simply to drop seeds from a drone; there are many issues once the seeds are on the ground that have to be taken into account to guarantee restoration success. In fact, broadcast seeding is an old method for forest restoration, and the use of aircrafts in this practice was common since the 1950s (Pedrini et al. 2020). Its effectiveness, however, is largely variable (e.g. Espelta et al. 2003; Shannon & Elliott 2020), due among other things to the fact that most seeds will fall in hostile microsites for recruitment. Current seed technologies to protect seeds or promote germination and seedling establishment are helping to overcome some of these barriers (e.g. Pearson et al. 2019; Pedrini et al. 2020), but even so, a massive firing of seeds from drones may not be the best solution to restore the forest. The real potential of drone seeding is the ability to deliver seeds precisely where it is most likely that recruitment will occur, thereby reducing seeding rates and maximizing success (Castro et al. 2021). This may be achieved by dropping the seeds in specific locations (e.g. specific microhabitats) where chances for seedling recruitment are maximized through microclimatic amelioration or promotion of positive biotic interactions. This would need a fine-grained map of habitat and microhabitat suitability at the submeter scale, a task that can currently be achieved thanks to remote sensing technologies (Castro et al. 2021). Moreover, it might even be automated with algorithms of artificial intelligence that could allow for the recognition of specific safe sites (e.g. nurse plants) for seedling establishment (e.g. Guirado et al. 2017). We still need a lot of research on these aspects, with controlled experiments that test the recruitment success from drone seeding in at least the medium term and, similarly, the potential side effects on biota. In the meantime, we should not suggest that forest restoration is achieved by dropping seeds from drones, however much we may prepare those seeds to increase establishment success. We usually consider technological solutions to be better than those existing up to that point, and we tend to trust them blindly. This is making seeding with drones a goal in itself. However, we should not forget that in the context of forest restoration, drone seeding is a tool, not an objective per se.

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LITERATURE CITED

Aghai M, Manteuffel-Ross T (2020) Enhancing direct seeding efforts with unmanned aerial vehicle (UAV) "swarms" and seed technology. Tree Planters' Notes 63:32–48

Boydak M (2003) Regeneration of Lebanon cedar (*Cedrus libani* A. Rich.) on karstic lands in Turkey. Forest Ecology and Management 178:231–243. https://doi.org/10.1016/S0378-1127(02)00539-X

Bozzano M, Jalonen R, Thomas E, Boshier D, Gallo L, Cavers S, Bordács S, Smith P, Loo J (2014) Genetic considerations in ecosystem restoration using native tree species. The state of the world's forest genetic resources—thematic study. Food and Agriculture Organization of the United Nations, Rome, Italy

Burns RM, Honkala BH (1990) Silvics of North America. Volume 1. Conifers. Agriculture handbook 654. USDA Forest Service, Washington D.C.

Castro J, Zamora R, Hódar JA, Gómez JM (2004) Seedling establishment of a boreal tree species (*Pinus sylvestris*) at its southernmost distribution limit: consequences of being in a marginal Mediterranean habitat. Journal of Ecology 92:266–277. https://doi.org/10.1111/j.0022-0477.2004.00870.x

Castro J, Hódar JA, Gómez JM (2006) Seed size. Pages 397–427. In: Basra AS (ed) Handbook of seed science and technology. Haworth Press, New York

Castro J, Morales-Rueda F, Navarro FB, Löf M, Vacchiano G, Alcaraz-Segura D (2021) Precision restoration: a necessary approach to foster forest recovery in the 21st century. Restoration Ecology 29:e13421. https://doi.org/10.1111/rec.13421

Darwin CR (1859) On the origin of species by means of natural selection.

Espelta JM, Retana J, Habrouk A (2003) An economic and ecological multicriteria evaluation of reforestation methods to recover burned *Pinus nigra* forests in NE Spain. Forest Ecology and Management 180:185–198. https://doi.org/10.1016/S0378-1127(02)00599-6

Fagan ME, Reid JL, Holland MB, Drew JG, Zahawi RA (2020) How feasible are global forest restoration commitments? Conservation Letters 13:e12700. https://doi.org/10.1111/conl.12700

FAO (2020) The state of the world's forests 2020. FAO, Rome, Italy

Garcia JM, Bordignon AM, Gonzaga GS, Torezan JMD (2020) Tree seedling responses to leaf-cutting ants herbivory in Atlantic Forest restoration sites. Biotropica 52:884–895. https://doi.org/10.1111/btp.12808

Guirado E, Tabik S, Alcaraz-Segura D, Cabello J, Herrera F (2017) Deep-learning versus OBIA for scattered shrub detection with Google earth imagery: *Ziziphus lotus* as case study. Remote Sensing 9:1220. https://doi.org/10.3390/rs9121220

Harper JL (1977) Population biology of plants. Academic Press, London, UK

Herrero A, Castro J, Zamora R, Delgado-Huertas A, y Querejeta JI (2013) Growth and stable isotope signals associated with drought-related mortality in saplings of two coexisting pine species. Oecologia 173:1613–1162. https://doi.org/10.1007/s00442-013-2707-7

Holl KD, Lulow ME (1997) Effects of species, habitat, and distance from edge on post-dispersal seed predation in a tropical rainforest. Biotropica 29:459–468. https://doi.org/10.1111/j.1744-7429.1997.tb00040.x

Hulme PE (1998) Post-dispersal seed predation: consequences for plant demography and evolution. Perspectives in Plant Ecology, Evolution and Systematics 1:32–46. https://doi.org/10.1078/1433-8319-00050

Hunt C (2008) Economy and ecology of emerging markets and credits for biosequestered carbon on private land in tropical Australia. Ecological Economics 66:309–318. https://doi.org/10.1016/j.ecolecon.2007.09.012

Koski V (1991) Generative reproduction and genetic processes in nature. Pages 59–72. In: Giertych M, Mátyás C (eds) Genetics of Scots pine. Akadémiai Kiadó, Budapest, Hungary

Krauss KW, Lovelock CE, McKee KL, López-Hoffman L, Ewe SM, Sousa WP (2008) Environmental drivers in mangrove establishment and early development: a review. Aquatic Botany 89:105–127. https://doi.org/10.1016/j.aquabot.2007.12.014

Leverkus AB, Castro J, Puerta-Piñero C, Rey-Benayas JM (2013) Suitability of the management of habitat complexity, acorn burial depth, and a chemical repellent for post-fire reforestation of oaks. Ecological Engineering 53: 15–22. https://doi.org/10.1016/j.ecoleng.2013.01.003

Lopez-Antia A, Feliu J, Camarero PR, Ortiz-Santaliestra ME, Mateo R (2016) Risk assessment of pesticides seed treatment for farmland birds using refined field data. Journal of Applied Ecology 53:1373–1381. https://doi.org/10.1111/1365-2664.12668

Mansourian S, Berrahmouni N, Blaser J, Dudley N, Maginnis S, Mumba M, Vallauri D (2021) Reflecting on twenty years of forest landscape restoration. Restoration Ecology 29:e13441. https://doi.org/10.1111/rec.13441

Mohan M, Richardson G, Gopan G, Aghai MM, Bajaj S, Galgamuwa GA, et al. (2021) UAV-supported forest regeneration: current trends, challenges and implications. Remote Sensing 13:2596. https://doi.org/10.3390/rs13132596

Nelson JR, Wilson AM, Goebel CJ (1970) Factors influencing broadcast seeding in bunchgrass range. Journal of Range Management 23:163–170. https://doi.org/10.2307/3896379

Novikov AI, Ersson BT (2019) Aerial seeding of forests in Russia: a selected literature analysis. IOP Conference Series: Earth and Environmental Science 226:012051. https://doi.org/10.1088/1755-1315/226/1/012051

Pearson DE, Valliant M, Carlson C, Thelen GC, Ortega YK, Orrock JL, Madsen MD (2019) Spicing up restoration: can chili peppers improve restoration seeding by reducing seed predation? Restoration Ecology 27:254–260. https://doi.org/10.1111/rec.12862

Pedrini S, Merritt D, Dixon K (2020) Smart seed for automated forest restoration. Pages 113–128. In: Elliott S, Gale G, Robertson M (eds) Automated forest restoration: could robots revive rain forests? FORRU-CMU, Chiang Mai, Thailand

Peet RK, Christensen NL (1987) Competition and tree death. BioScience 37:586–595. https://doi.org/10.2307/1310669

Philipson CD, Cutler ME, Brodrick PG, Asner GP, Boyd DS, Moura Costa P, et al. (2020) Active restoration accelerates the carbon recovery of human-modified tropical forests. Science 369:838–841. https://doi.org/10.1126/science.aay4490

Poliserpi MB, Cristos DS, Brodeur JC (2021) Imidacloprid seed coating poses a risk of acute toxicity to small farmland birds: a weight-of-evidence analysis using data from grayish baywing *Agelaioides badius*. Science of the Total Environment 763:142957. https://doi.org/10.1016/j.scitotenv.2020.142957

Savill P, Evans J, Clair DA, Falck J (1997) Plantation silviculture in Europe. Oxford University Press, Oxford, United Kingdom

Shannon DP, Elliott S (2020) Developing aerial seeding by UAVs: lessons from direct seeding. Pages 75–83. In: Elliott S, Gale G, Robertson M (eds) Automated forest restoration: could robots revive rain forests? FORRU-CMU, Chiang Mai, Thailand

Takatsuki S (2009) Effects of sika deer on vegetation in Japan: a review. Biological Conservation 142:1922–1929. https://doi.org/10.1016/j.biocon.2009.02.011

Van Nedervelde F, Canicci S, Koedam N, Bosire J, Dahdouh-Guebas F (2015) What regulates crab predation on mangrove propagules? Acta Oecologica 63:63–70. https://doi.org/10.1016/j.actao.2014.11.006

Wang J, Wang GG, Zhang T, Yuan J, Yu L, Zhu J, Yan Q (2021) Use of direct seeding and seedling planting to restore Korean pine (*Pinus koraiensis* Sieb. et Zucc.) in secondary forests of Northeast China. Forest Ecology and Management 493:119243. https://doi.org/10.1016/j.foreco.2021.119243

Supporting Information

The following information may be found in the online version of this article:

Table S1. Summary of some reports that have appeared in the media of different countries across several continents.

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