Enhancing Direct Seeding Efforts With Unmanned Aerial Vehicle (UAV) “Swarms” and Seed Technology

Matthew Aghai and Tiffani Manteuffel-Ross

Director of Biological Research & Development, DroneSeed Co, Seattle, WA;
Research Scientist, Biological Research & Development, DroneSeed Co, Seattle, WA

Abstract

Technological advances of unmanned aerial vehicles (UAVs) are creating new possibilities for establishing trees and native plants across large areas and have the potential to serve as a rapid response tool in post-disturbance environments. The advanced machinery and automation are also extending the possibility for “enhanced” seeding methods as an intermediate between conventional direct seeding and planting of nursery stock. This approach may allow managers to overcome limitations of cost, labor, safety, and viability. Here we present components of our novel software, hardware, and seeding systems designed to address payload delivery efficiently, precisely, safely, at scale, and within the regulatory framework of the United States Federal Aviation Administration.

Introduction

Artificial regeneration approaches for landscape management must meet myriad ownership objectives and account for economic, regulatory, and ecological considerations. Seeds are often the basis for artificial regeneration, whether as the first step in a nursery’s investment in a seedling or applied directly on the landscape with little other intervention. Direct seeding for reforestation and native plant restoration is currently used in cases where rapid response is necessary (e.g., soil stabilization with grasses, Kruse et al. 2004, Peppin et al. 2010), where the ecology of a species regenerated from seed contributes to sound silvicultural practice (e.g., a reduction in lag time for establishing appropriate species and stocking goals), or where restoration objectives (e.g., vegetation/canopy cover or habitat) can be met.

In forest operations, direct seeding is relatively fast to implement, but several disadvantages lead to a nearly 80-percent failure for individual seeds, and greater than 50-percent failure by project to meet stocking targets (Grossnickle and Ivetić 2017). Direct seeding, however, can be more cost effective at scale (Baumhauer et al. 2005) with some recent research highlighting up to a 64-percent reduction in reforestation costs (Pérez et al. 2019). Historically, direct seeding in forestry has been used successfully to meet landscape objectives where high volumes of seed are deployed with the expectation that poor survival and self-thinning will lend to appropriate stocking (Ceccon et al. 2016, Duryea 1987, Palma and Laurance 2015, Scott 1970). Alternatively, in restoration efforts, particularly for large-scale projects, direct seeding is the primary revegetation approach because it is typically 10 to 30 times cheaper than planting nursery stock (Masarei et al. 2019) and is less labor intensive. Difficulties for direct seeding also exist in restoration, including high incidence of desiccation, predation, and wind erosion that contribute to low plant establishment rates—ranging from 10-percent emergence to outright failure (Commander et al. 2013, Masarei et al. 2019, Merritt and Dixon 2011).

Although direct seeding can be practical, low cost, and responsive to immediate need, conventional approaches of this method have been impeded by crude dispersal mechanisms, coarse spatial distribution techniques, and unrefined seed handling (Grossnickle and Ivetić 2017). For large treatment areas, from rangelands to large post-disturbance forestry units, seed deployment is often non-uniform when applied using aerial systems with broadcasting machines, sling-pod buckets, or boom dispersing systems (Hallman and Larson 1980). For example, the distribution of most aerially broadcast seed is highly irregular when using airplanes and helicopters due to aircraft speed, bridging or jamming in hoppers, and scattering as influenced by propeller or rotor wash or the aerodynamic properties of the seed (Becker 2001). Additionally, after seed lands on the ground, a number of abiotic and biotic factors can limit germination, survival, viability, and persistence. Without controlled selection of microsites, a large amount of aerially broadcast seed lands in unsuitable or inhospitable places that will not support plant establishment (e.g., surface rock or large woody detritus and erosion-prone or crusted surfaces). Surface deposition of seed is at a risk of predation, undesirable seed transport from wind or precipitation, and potential damage or mortality from desiccation (Gornish et al. 2019, Madsen et al. 2016). Where ground-based machine access is possible, seed can be deployed using tractors with drill-seeding attachments or other agricultural-style equipment, with the intent of achieving some control over subsurface seed placement resulting in potentially higher establishment rates (Masarei et al. 2019).

A consequence of seeding using conventional systems is the loss of substantial quantities of seed. Seed is an increasingly valuable commodity to various industries, including governments, resource companies, and nonprofit organizations, as they position themselves for addressing large climate change mitigation efforts and landscape-scale restoration efforts through increased planting (Broadhurst et al. 2016, Jalonen et al. 2016, Nevill et al. 2016). Given the increased size and frequency of disturbances on the landscape due to climate change-driven phenomena like wildfire, beetle-kill, drought (Seidl and Rammer 2017, Stephens et al. 2014), and the reduced likelihood of natural regeneration from seed rain and recruitment (Kemp et al. 2016, 2019), seed-use efficiency is tantamount to sustainable land-management practices and risk mitigation. Updating the technology and methods of direct seeding provides an opportunity for reduced seed usage, improved spatial distribution and targeting, and greater survival outcomes for direct seeding in forest, restoration, and rangeland settings (Grossnickle and Ivetić 2017, Maserai et al. 2019).

Technological advances of unmanned aerial vehicles (UAVs) are creating new possibilities for natural resources management. This technology gives the ability to survey a landscape, use high-quality aerial imagery to classify sites, then deploy materials (such as seed) over large areas quickly and efficiently with battery-powered, propeller-based aircraft that use slow flight speeds and are highly maneuverable (figure 1). Until recently, use of UAVs for reforestation and restoration work has been limited to imaging for reconnaissance and monitoring (for regulatory and technological reasons, see Baena et al. 2018, Belmonte

Figure 1. A DroneSeed custom-engineered hexacopter (patent pending) capable of carrying up to 57 lb (25 kg) of payload with an “all-up” weight up to 115 lb (52 kg). This aircraft is typically flown autonomously as part of multiple, coordinated, high-capacity, autonomous aircraft, also known as “swarms,” and operated by a limited number of ground personnel to service battery and payload replacements between missions. (Photo courtesy of DroneSeed 2019)

et al. 2019, Sankey et al. 2017); however, unmanned commercially available aircraft are increasingly becoming capable of achieving precise direct seeding on complex and remote landscapes.

Technological and Regulatory Limitations

According to the Federal Aviation Administration (FAA) regulations (USDOT 2020), a typical commercial UAV is restricted to an all up weight of 57 lbs (25 kg), and pilots can only fly a single aircraft in which they must maintain "line-of-sight" of the UAV unless they have a waiver or exemption (identified as Federal statutes as "part #" waivers). Typical commercial UAVs are also usually limited by technological capacity (hardware limitations) to flight times of 15 minutes (internal DroneSeed communication). These regulatory restrictions limit acreage, operational ability, and payload (herbicide, seed, etc.) size in a given flight, creating a mismatch between the application capacity and treatment need, because many management units cover vast areas. The seemingly simple exercise of increasing the number of drones and corresponding operators will not directly result in incremental improvements to throughput.

A pathway to working on the landscape scale of significant acres with UAV systems requires technology to achieve "swarm" operations. Swarms are multiple, coordinated, high-capacity, autonomous aircraft, operated by a limited number of ground personnel. Thus, for resource management beyond remote sensing, revegetation operations with UAV swarms need to meet several primary requirements: (1) ability to carry substantial weight (payloads) with support systems (such as battery charging systems) to prioritize flight over time aircraft are on the ground; (2) regulatory consent to scale operations to multiple coordinated UAVs over long distances and beyond visual line of sight; (3) UAV programmability through targeted software development; and (4) improved handling, deposition, and efficiency of seed dispersal.

Seed Distribution and Enablement Technology

Handling, delivery, and efficacy of materials (e.g., seed) deployed from UAVs also needs improvement. Aerial broadcast systems, to date, have largely relied on attachments that can be described as hopper-fed buckets with a motorized sling that emit seed in a coarse manner (Stevens 1999). These systems further rely on the aircraft's altitude, speed, and GPS accuracy to achieve their target seeding rates, often on difficult or remote terrain. In direct seeding efforts, multi-species mixes can be composed of forbs, grasses, and shrub seeds with a wide range of sizes and morphologies. During aerial broadcasting, seed mixtures are subject to intense vibrations that can cause segregation by size and species, and mechanical processes that are unable to precisely control flow rate, often resulting in uneven seed distributions (Becker 2001). To stabilize seed and normalize distribution patterns, seed can be coated or pelleted as individual seed or agglomerates (Madsen et al. 2016, Masarei et al. 2019, Pedrini et al. 2020). While many seed coating and processing technologies have been applied to native plant species for easing the aerial seeding process, these technologies have rarely been applied to forest tree seed (particularly conifers) (Grossnickle and Ivetić 2017).

A holistic approach to seed technology should increase the probability of seed germination, root egress, and plant establishment without hindering the evolutionary potential of that particular species. To mitigate predation of the seed, seed-coating amendments can include olfactory and/or gustatory deterrents (Pearson et al. 2018), camouflaging agents (Porter 2013, Van Damme 1988), and/or masking agents and physical barriers (Taylor et al. 2020). Efficacy of seed treatments as a predation deterrent should be mindful of regulatory standards, and trophic consequences of toxic/noxious properties. Beneficial seed-coating amendments should enable the survival and development process, including a rooting substrate, nutrients, phytohormones, mycorrhizal and bacterial symbionts, all of which can mitigate desiccation and other limiting edaphic conditions.

Developing successful seed treatments will require a thorough understanding of species-specific biological traits, such as seed morphology, dormancy requirements, and viability, in addition to site-specific biotic and abiotic conditions that will impact seed after deposition. To date, direct seeding efforts—particularly with native plants—have employed a wide range of treatments. Controlled stratification (Barnett 2014) and/or dormancy alleviation treatments (Kildisheva 2019, Kildisheva et al. 2020) can enable better germination and establishment. A number of experiments and field operations have evaluated poisons, chemical deterrents, and supplementary feeding to alleviate predation from granivores (Campbell 1981, Sullivan 1979). A shift in environmental laws and best practices has more recently led to an exploration of plant-derived deterrents like capsaicin (i.e., hot pepper), activated carbon, or essential oils (Taylor et al. 2020).

DroneSeed Case Studies

Much of the equipment, infrastructure, and software required for the premise of swarm operations did not exist when DroneSeed began operations in 2016. Our interdisciplinary team (composed of software and hardware engineering, aviation, forestry, geographic information systems, and ecology professionals), based in Seattle, WA, is advancing the UAV-based aerial-seeding technology and techniques. Our customers' typical "pain-points" include the need for large-scale, post-disturbance (specifically wildfire) revegetation/stabilization tools, difficulty accessing remote and rough terrain, limited labor pools or the increasing costs of planting, stressful site conditions (e.g., drought), and the high cost of planting stock. Our team has developed a number of novel solutions for UAV-based revegetation, including software guidance systems, hardware such as aircrafts and support vehicles with power systems, and standard operating procedures to safely sustain operations. Our multi-component process (figure 2) can provide landowners and managers with a comprehensive survey, payload delivery, and

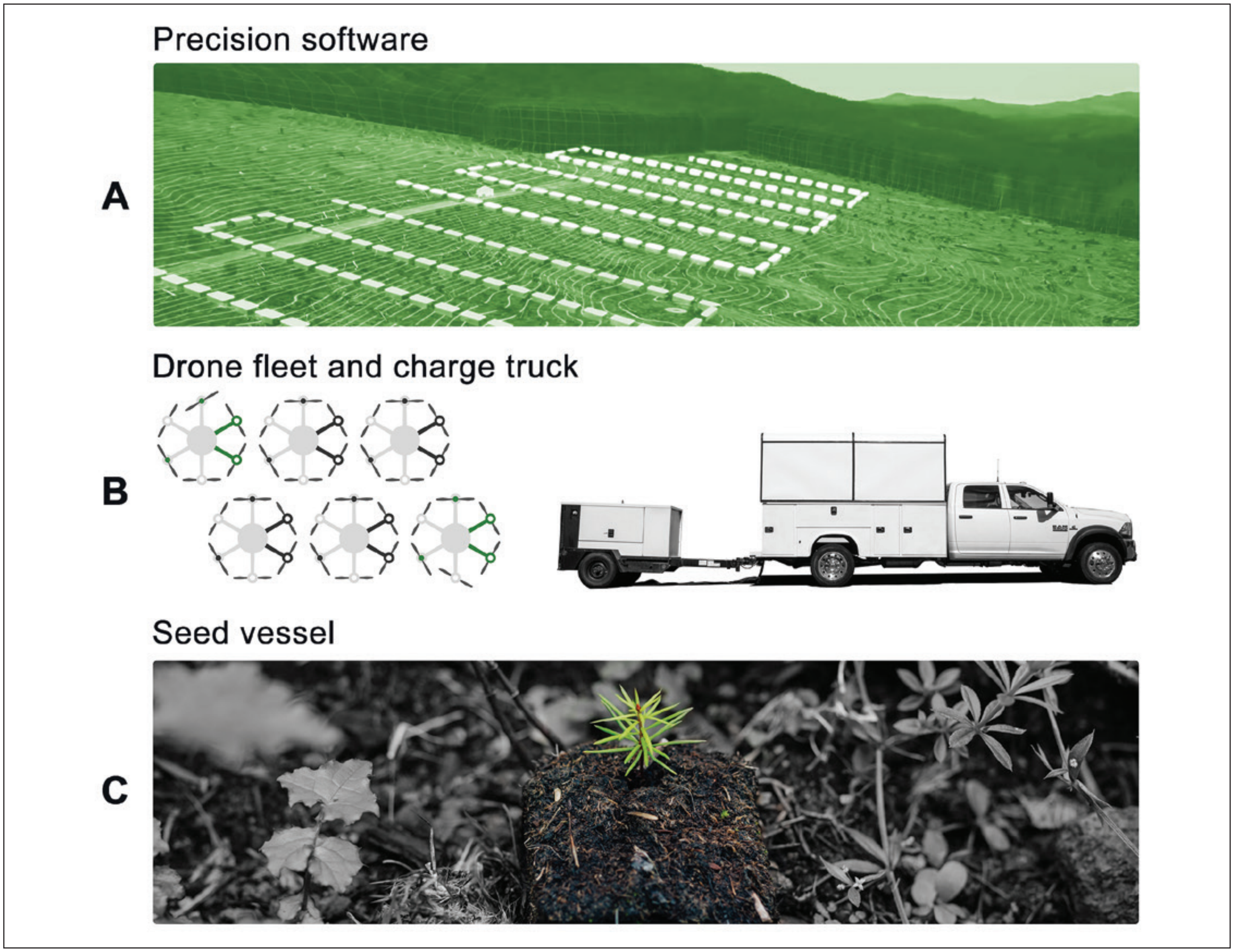

Figure 2. DroneSeed's three-part solution (patent pending) for revegetation consists of (a) proprietary software to survey, create swarm flight plans, and identify areas for seed deployment; (b) mobile charging truck that can keep five drones that each carry a 57 lb (25 kg) payload continuously in the air; and (c) seed vessels— "pucks"—that can boost seedling survival rate by reducing predation and desiccation. (Images courtesy of DroneSeed 2020)

monitoring solution for myriad site conditions and terrain complexities.

The following case studies, presented in chronological order, capture the onset of our program development for aerial seeding from mid-2018 through late 2019 when we began to service larger land areas with the technology. The case studies intend to provide the reader with an overview of the early development process and application of our technology as we use rapid scaling and adaptive management to continue to develop tools for forest managers and restoration practitioners.

Case Study 1: Payload Size and Line of Sight Waivers

Since 2017, DroneSeed has achieved a number of precedent-setting regulatory approvals to pioneer the swarm-based revegetation platform. DroneSeed's first waiver was a 15-aircraft "swarm" waiver, under FAA part 107. Aircraft in this waiver must be under 55 lb (25 kg) and are allowed to be flown by one pilot. Achieving the part 137 (to dispense fertilizer, herbicides, and water for up to five aircraft under 55 lb [25 kg]) required a "Knowledge and Skills" test in which the chief pilot commands an aircraft in front of FAA inspectors from one of the regional Flight Standards District Offices (FSDO).

Late in 2018, we set another precedent in the heavy-lift UAV industry by achieving the over-55 lb (25 kg) per aircraft swarm (FAA part 137 approval). This approval granted us the ability to fly up to five aircraft, each with a 57-lb (25.9 kg) payload and total weight of 115 lb (52 kg) with one pilot. The waivers were granted to deploy herbicides and other registered products from the aircraft, specifically seed and seed vessels conducive to revegetation operations. In 2019, the latest regulatory permission allowed DroneSeed to conduct field operations that require beyond visual line of site (BVLOS) capability. A summary of regulatory achievements can be found in table 1.

Case Study 2: Biotechnology ("Pucks") for Seeding

We developed biotechnology for seeding methods intermediate to direct seeding and planting nursery stock (figure 3) that can be deployed by UAVs to address key establishment issues. We created manufacturing processes for customized seed treatment and embedding into vessels ("pucks") to optimize seedling germination and establishment after dispersal from the aircraft. The pucks consist of a fiber-based substrate and provide risk-mitigating amendments to the seed (e.g., to reduce predation). The puck substrate simulates optimum seeding depth and acts as a germination bed on site, providing optimal pH, some water retention, and addition of beneficial abiotic and biotic amendments for germination and seedling establishment.

The puck, named for its appearance and compressed configuration when dry, is not a "one-size-fits-all" technology, as different ecosystems and species require different base materials, amendments, and configurations. Current sizes range from the smaller

Table 1. Summary of DroneSeed regulatory achievements with corresponding dates and descriptions.

Agency	Permission/waiver*	Date obtained	Description
FAA	Part 107	11-16-2016	Allows 1 pilot to fly 15 drones under 55 lbs simultaneously
FAA	Part 137	3-17-2017	Allows dispensing pesticides with drones under 55 lbs
FAA	Part 137	4-25-2017	Allows dispensing pesticides with drones over 55 lbs
FAA	333 Exemption	8-13-2018	Allows 1 pilot to fly 5 drones over 55 lbs simultaneously
FAA	333 Exemption	9-11-2018	Allows 1 pilot to fly 5 drones over 55 lbs simultaneously and added a DroneSeed aircraft type to permissions
FAA	333 Exemption	7-26-2019	Allows Beyond Visual Line of Site operations

*Further detail on regulatory information can be found at https://www.faa.gov/uas/

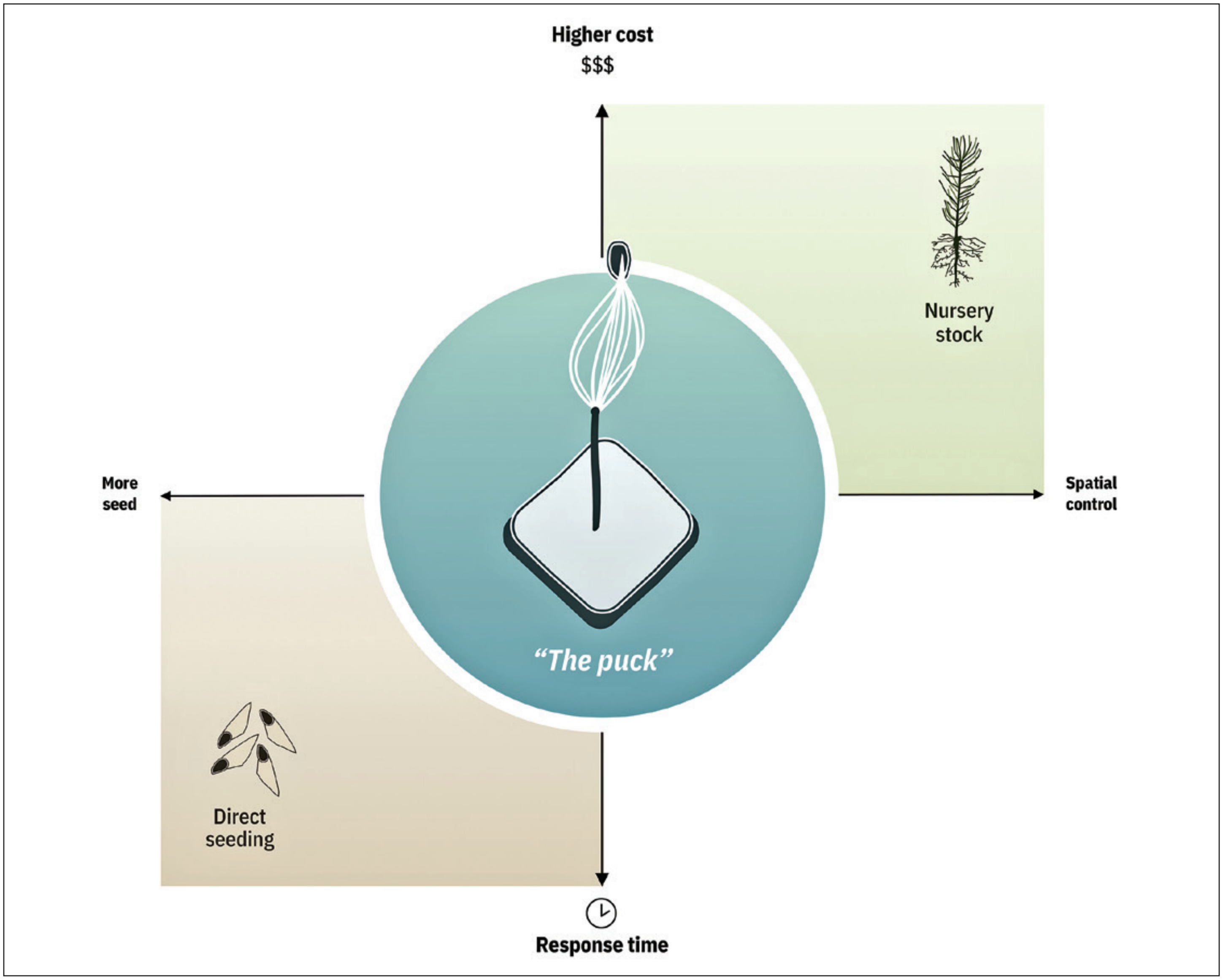

Figure 3. DroneSeed enablement strategy is a fiber-based vessel ("puck") with amendments suited to species and site conditions designed to increase seed germination and seedlings establishment (patent pending). The puck is designed to be an intermediate product between conventional direct seeding and nursery stock options for artificial regeneration. (Image courtesy of DroneSeed 2020)

2 by 2 by 0.4 in (5 by 5 by 1 cm) up to the largest 27 by 27 by 2 in (70 by 70 by 5 cm). Additional puck dimensions are developed to meet new species and ecosystem needs as the customer base expands—typically a 3-month process is required to meet scalable manufacturability for a new configuration. In addition to the puck, species-specific treatments are applied directly to seeds to alleviate dormancy (as needed), or to add coatings to decrease risk of predation, pathogens, and desiccation.

As a payload, the homogenous puck has advantages including a consistent quantity of seed, easier transport and deployment, and reliable behavior after deployment. Additionally, the puck lends itself to rapid and efficient manufacturing, packaging, and reloading of the aircraft between missions. During manufacturing, we track seed lot information (e.g., provenance, elevation, age, germination rate, etc.), seed treatment, and amendment information all the way to the deployment site.

Since the technology is novel, limited field data are available. Using greenhouse and bench trials prior to operations and accounting for significant mortality rates common in true field conditions, we set initial seeding rates for a species and calibrate in subsequent operations with similar species and edaphic conditions. Much of the development work has centered on puck functionality for conifer systems, with ponderosa pine

(*Pinus ponderosa* Lawson & C. Lawson) serving as the model species. Typically, three or more conifer seeds are amended into the puck, with up to six seeds per puck. A prescriptive range of 500 to 2,000 pucks may be applied per acre (1,250 to 5,000 pucks per hectare), with the intention of achieving up to 20-percent survival and establishment without overstocking a unit. With native plant seed, variation is higher, as grass, forb, and shrub species have variable seed characteristics. Higher seed quantities can be used by changing the configuration of the puck during production.

Since DroneSeed first developed and field-tested the pucks in 2018, a variety of commercial project sites have been seeded with more than 400,000 pucks. To expedite availability of data on puck performance, DroneSeed manufactured early versions and deployed them in small trials in the northern and southern hemispheres to generate two growing seasons of data regarding puck performance, as described in the following sections.

Trial Site: Southwestern Washington State USA

DroneSeed was granted access to a 5-ac (1.6-ha) recently harvested site on the University of Washington Pack Experimental Forest to test microsite variables in relation to seedling emergence from DroneSeed's proprietary puck. The Pack Forest is located in the foothills of Mt. Rainier, approximately 50 miles (80 km) southeast of Seattle, WA, and is dominated by second growth Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco).

A total of 40 unequal-size plots were installed across 1 ac (0.4 ha) on September 24 and 25, 2018. Quadrats followed an east-west and elevational gradient and varied in size to increase relative proportion of exposed mineral soil (figure 4). A total of 1,000 early-version (V1, table 2) peat-based puck prototypes were used in this test, 25 per plot in groups of 5 to 10. Microsites were identified as locations with "nurse materials" along stumps and next to downed logs or coarse, woody detritus, but also as exposed patches of mineral soil. In plots where microsites were not available (or less present), pucks were placed randomly on surface conditions which included duff, slash, or fine woody detritus. The "clusters" were located with a Tersus GPS for tracking purposes.

Three Douglas-fir seeds of local provenance were embedded into each puck. No deterrents, fertilizers, or fungicides were included in this "beta" test.

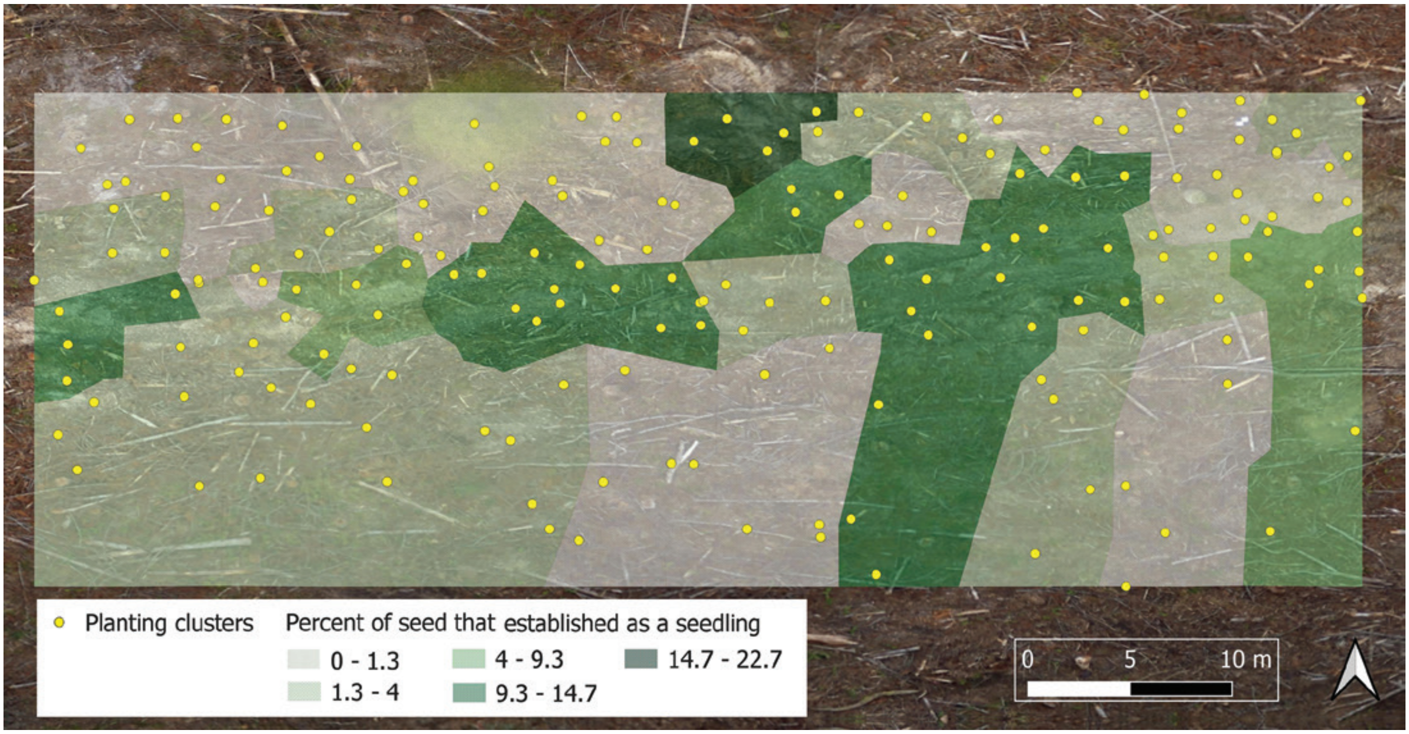

Figure 4. A trial site segmented by seeding quadrants where the puck with Douglas-fir (Pseudotsuga menziesii Mirb. Franco) seed was deployed at 25 per quadrant. The figure is color coded to represent percentage establishment 12 months after seeding. Note the faintly visible edaphic conditions, including extensive debris and post-harvest conditions. It appears that mineral soil exposed by logging skid tracks is correlated to increased percentage of established seedlings (see figure 5). (Photo courtesy of DroneSeed 2018)

Table 2. Versions and corresponding features and amendments of the DroneSeed "puck," a seed-planting vessel used to improve likelihood of seed germination and establishment.

Seed vessel version (year deployed)	Design features and amendments
"Beta" - Version 1 (2018)	Fiber-based pellet Single-sided seed configuration pH stabilized
"V2" - Version 2 (2018)	Fiber-based pellet Double-sided configuration pH stabilized
"V3" - Version 3 (2019)	Fiber-based pellet Double-sided configuration pH stabilized Olfactory and gustatory predatory deterrents (plant-based)
"V4" - Version 4 (2019)	Fiber-based pellet Double-sided configuration pH stabilized Olfactory and gustatory predatory deterrents (plant-based) Pathogen risk mitigation
"V5" - Version 5 (2020)	Advanced materials for fiber-based pellet (2 varieties) Double-sided configuration pH stabilized Olfactory and gustatory predatory deterrents (plant-based) Enhanced manufacturing process for amendments/seed Nutrients and beneficial organisms (optional) Biochar and other carbon or mineral material supplements (optional)

Prior to manufacturing, a subset of seed was stratified (surfaced sterilized with bleach, then soaked for 48 hours followed by storage at 3 ˚C for 30 to 90 days, at high relative humidity, see Dumroese et al. 1988). Each puck had one unstratified (dormant from storage) and two stratified seeds, as a means of bet-hedging. Pucks were transported to the project site and deployed by hand within 48 hours of manufacturing.

Throughout the 2019 growing season, we monitored seedlings emerging from pucks and distinguished them from seed rain from nearby mature canopy. We determined seedlings had germinated from our pucks based on known puck locations, puck residue surrounding seedlings, and seedling age.

At the final measurement (September 2019), 14 percent of the pucks produced seedlings within a 12-month period. Given that there were 3 seeds per puck for this trial, this translates to a 4.7-percent seedling to seed ratio. Grossnickle and Ivetic (2017) found the average seedling establishment rate of 16 percent (range of 0 to 52 percent calculated as survival rate following >1 growing season per/total number of seeds planted) with temperate conifers, influenced by biotic pressure (predation and competition), seedbed receptivity (microsites), and seed viability. In our trial, plots with majority mineral soil had the highest survival and those with a majority of slash had the lowest survival (figure 5). It is likely that this new mineral soil in skid tracks from cable logging and other harvesting operations improved soil contact and water or nutrient availability (Barker et al. 2014).

This particular site represented relatively difficult regeneration conditions due to recalcitrant native vegetation (e.g., sword fern [*Polystichum munitum* (Kaulf.) C. Presl] and Oregon grape [*Mahonia aquifolium* (Pursh) Nutt.]), heterogeneity in surface conditions, and the lack of site preparation. Additionally, the trial site was surrounded by undisturbed second growth forest, which likely increased granivore predation (anecdotal evidence of rodent activity was captured on game cameras placed on the site).

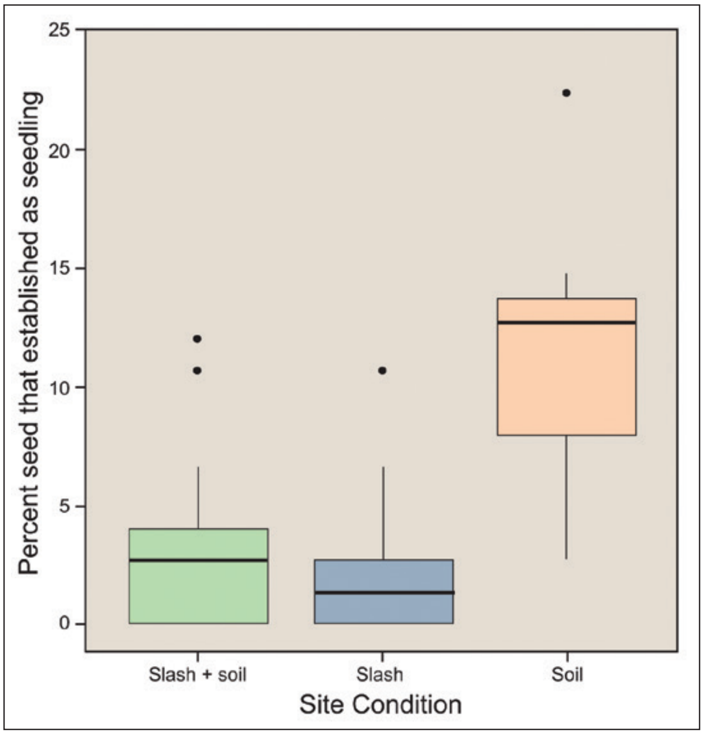

Figure 5. In a comparison of edaphic conditions, mineral soil conditions appear most favorable for rooting and establishment of seedlings from pucks.

Trial Site: New Zealand

In 2019, DroneSeed established several test plots using approximately 10,000 V3 pucks (table 2) across the North and South Islands of New Zealand. Three species were included: radiata pine (*Pinus radiata* D. Don), Douglas-fir, and mānuka (*Leptospermum scoparium* J.R. Forst. & G. Forst.), all with significant economic and ecological relevance to the region and reciprocal regions where DroneSeed operates. Radiata pine and Douglas-fir are the primary timber species commercially grown across New Zealand, and mānuka is a fast-growing plant native to New Zealand that has been subject to many eradication efforts over the last century but is now the focus of many commercial and restoration planting efforts because of its applications as a soil stabilizer, an important ecosystem component, and a major contributor to the oil and honey (pollinator) marketplace (Stephens et al. 2005).

A total of 16 plots were established across seven ownerships, on both the North and South islands. The sites ranged from cutover forestland (recent harvests), to earthquake-damaged hillsides, to pastureland that was slated for afforestation. Each test plot was approximately 2.5 acre (~1 ha) and was selected on the basis of recent disturbance (harvest or erosion) or vegetation-clearing by grazing stock (pasture). We stratified our experiments latitudinally across both islands, thus providing a variety of climatic, edaphic, and biophysical conditions. No chemical site preparation was implemented prior to deploying the pucks, but grazing animals were allowed access on some plots ahead of the trial.

Pucks and materials were shipped to New Zealand, where a local group finished the manufacturing process. All pucks included amendments intended to deter granivore predation (table 2). There were two treatment groups for radiata pine (either stratified or dormant seed treatments), two treatment groups on two site types for Douglas-fir (also either stratified and dormant seed), and one untreated group for mānuka. The radiata pine and Douglas-fir had four seeds per puck. The mānuka seed averaged ten seeds per puck.

Over a 10-day period in August 2019, pucks were hand distributed over the 16 plots. The distribution of blocks and transects varied to match the landform, vegetation status, and edaphic conditions provided by landowners for testing. In pasture rehabilitation areas or on erosion points, for example, a randomized block distribution was used to capture variability over a concentrated area of interest. In operational forestry settings, multiple pucks were distributed per point over long transects between rows of planted seedlings and/or between rows of slash.

In November 2019, we collected data to estimate puck residual material, survived seedlings, microsite presence/absence, and edaphic conditions, along with any relevant supplementary observations. No pucks of conifers had more than a single seedling. In cases where multiple pucks were deployed per point, multiple seedlings were present and counted individually. In the case of mānuka, we counted each puck as a single seedling, although there were often more than five emerged plants per puck (figure 6).

In 11 of the 16 plots, the outcomes met our operational hypothesis that survival (pucks with an established seedling) would be less than 5 percent by quantity of pucks deployed for each plot. In the other five plots, survival (established seedlings at the time of monitoring) exceeded 5 percent of all pucks deployed, and in some cases up to 37 percent of pucks deployed resulted in seedlings (table 3). The

Table 3. Range of results from 16 plots installed in New Zealand to trial an early version of the DroneSeed “puck.” Pucks were distributed to plots in early August and measurements were collected in late November 2019.

Species	Seed treatments	Sample size[1]	Number of plots	Site types	Seed to seedling ratio (percent established)	Percent of pucks with seedling establishment	Trees per acre[2]
Radiata pine	Stratified or dormant	500 to 1075	8	Cutover	0.1 to 3.7	0.4 to 14.8	3 to 159
Douglas-fir	Stratified or dormant	400	4	Pasture rehabilitation and cutover	0.1 to 1.1	0.5 to 4.3	2 to 17
Mānuka	N/A	550 to 565	4	Earthquake restoration	0.1 to 3.8	0.5 to 37.5	3 to 212

[1] Range of puck quantities per plot; mānuka was amended with approximately 10 seeds/puck; Douglas-fir and radiata pine were amended with 4 seeds/puck.

[2] Estimated established, per plot.

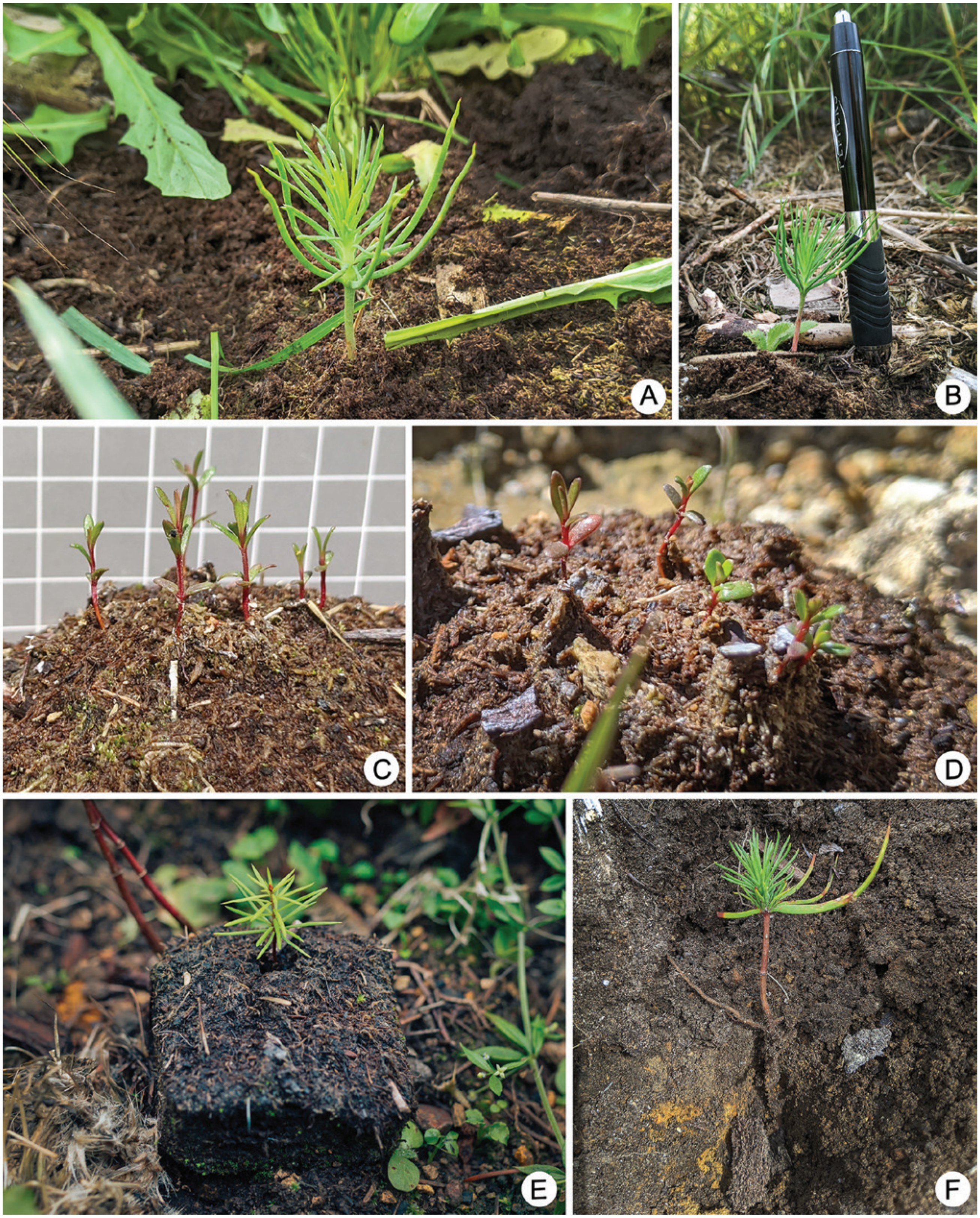

Figure 6. DroneSeed seed vessels (pucks) 6 months after deployment to field sites in New Zealand. (a) Radiata pine seedlings on degraded puck material. (b) Pen for scale next to a germinated radiata pine seedling. (c) Mānuka seedlings emerging from pucks in multiples with cm scale background grid. (d) Mānuka seedlings emerging from a degraded puck. (e) A single Douglas-fir emerged from a puck. (f) An excavated radiata pine seedling showing taproot egress and lateral root formation. (Photos courtesy of DroneSeed 2019)

Douglas-fir pucks averaged 1.6 percent seedling establishment (pucks with a seedling), radiata pine averaged 5.4 percent seedling establishment, and mānuka averaged 16.3 percent seedling establishment (table 3). Stratification was not implemented for mānuka, a typically photosensitive seed that had highly variable germination in our plots. Stratification improved Douglas-fir establishment, but not radiata pine (figure 7). Survival appeared to be primarily driven by moisture availability and soil type. On the South Island, where overgrazed or degraded clay soils were common, we saw a significantly limited germination rate. Clay soils limit surface water retention; so, while hydration of the pucks is possible during rain events, degradation or desiccation of the pucks due to surface flows or drying soils can occur between rain events. Other causes of low survival are likely predation and pathogens. While we did mitigate some predation with capsaicin deterrent, we did not account for potential damping off, or post-germination mortality from bird or insect predation (both of the latter were anecdotally observed).

A distinct observation from the test sites, and something we hope to demonstrate in future trials, is the correlation of microsites to survival and early development of seedlings. Depressions in the ground and shade from objects (e.g., woody detritus, adjacent vegetation, etc.) appeared to provide a favorable microclimate or shelter from predation.

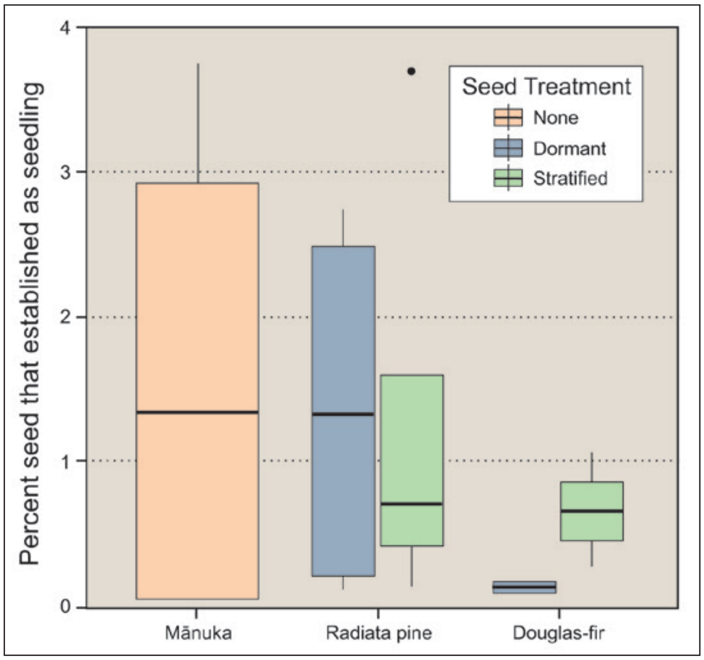

Figure 7. Seed germination from pucks varied by species across several plots in New Zealand. Stratification was critical for Douglas-fir seedlings but unnecessary for radiata pine.

Case Study 3: Custom UAV Systems and Operations for Dispersion of Seed

To carry a sufficient payload for successful vegetation management operations, we developed custom-engineered UAVs, using heavily modified, off-the-shelf components. Each UAV consisted of a central body housing a flight control computer, long-range telemetry radio, co-computer, redundant power supplies, redundant GPS modules, and batteries, with six radial arms supporting electric motors and propellers. Flight-control computers and long-range telemetry radios allow UAVs to receive pre-programmed flight plans and operate on autopilot, but with an observing pilot to take control if necessary. In 2019, when the next case study was completed, aircraft had a capable range of up to 7 mi (11.3 km), operating time of 8 to 18 minutes, and capacity to carry 57 lb (25.9 kg) per aircraft. The pucks deployed are tracked in a semi-controlled manner along a 3-m (10.8-ft) wide swath for each operational transect (figure 8), allowing for tracking genetic material from collection through revegetation.

Using a fusion of LiDAR (light detection and ranging), RGB (red, green, blue) imagery, and NIR (near infrared imagery), DroneSeed creates 3D models of a survey site, which can be used for planning heavy-lift swarm missions, but are also useful for many other survey objectives relevant to landowner objectives such as locations of site preparation, microsite and mineral soil identification, and general suitability of surfaces for seeding operations.

UAV-Assisted Artificial Regeneration

We were contracted in 2019 to survey and seed a unit that was part of the 2015 North Star Complex fire in northeastern Washington State. The property ownership experienced catastrophic, stand-replacing fire throughout the project area and well beyond those boundaries (Engel et al. 2019). The high-intensity fire resulted in almost complete destruction of the understory and canopy biomass, therefore limiting

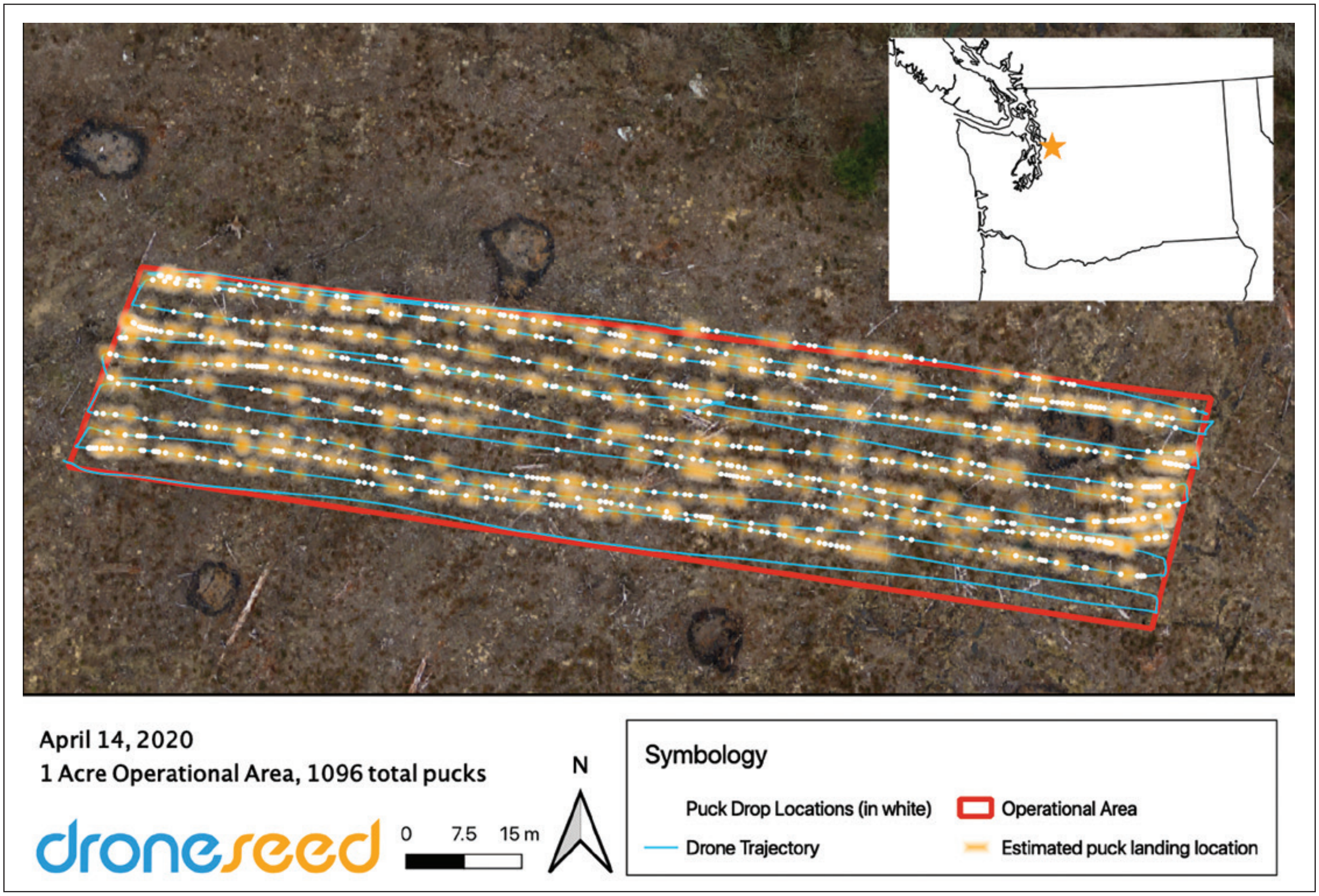

Figure 8. DroneSeed puck dispersion tracking is mapped and landing position is estimated within a 3-m swath using an onboard sensor system. This enables tracking of payloads with a high degree of accuracy from seed procurement and vessel manufacturing through to the field site. (Image courtesy of DroneSeed 2020)

opportunities for timely natural regeneration from seed rain. In subsequent years, recalcitrant native vegetation had grown to dominate the project area which had not yet reforested with conventional planting efforts.

The landowner objective was to establish economically and ecologically relevant stands of native trees across the unit. The edaphic conditions were deemed difficult and insufficient for conventional regeneration using nursery stock. The non-timber species dominating these conditions could not be controlled using chemical site preparation given the current regulatory situation on this ownership which prevents herbicide use based on environmental concerns. As an alternative to herbicide application, mechanical site preparation can create optimal edaphic conditions through scarification using excavators for turning over vegetation and surface materials, downing snags, collecting slash into concentrated points, and exposing mineral soil. Scarification was completed in fall 2019 (figure 9a) immediately prior to DroneSeed survey and seeding operations. We identified “No-Plant Zones” (NPZ) that were to be excluded from seeding due to substrate (e.g., large rocky outcroppings, moraine fields, etc.) and persistent vegetation cover (e.g., areas with dense, live canopy). We also excluded areas within the unit boundaries that were designated by the land manager to not be seeded, such as buffers around roads (figure 9b).

The land management provided a shapefile denoting the scarified area to be aerially surveyed for this project. Aerial drone survey with multispectral (RGB and NIR) and LiDAR imaging provided immediate insight into vegetation and soil status as well as landscape features (figures 10a and 10b). For the landowner, the aerial survey provided a series of high-resolution imagery data sets that can inform future land management practices. The LiDAR survey data informed UAV programming

Figure 9. (a) An aerial view of a DroneSeed customer site in northeastern Washington where mechanical scarification treatments removed vegetation that established over 4+ years following a large fire. (b) DroneSeed used multispectral survey imagery to designate no-plant zones and buffer roads (in red) to efficiently target optimal site conditions for seeding. (Photos courtesy of DroneSeed 2019)

for obstacle avoidance and terrain (figure 10c). The aerial survey data assisted with the development of a prescription for deploying enhanced seed over ground conditions that were most conducive to germination and establishment (such as site-prepped areas).

Seed for the project was provided by the land management 6 weeks prior to onsite operations so that manufacturing and assembly times for the pucks could be accommodated. Three species were included in this project: ponderosa pine, Douglas-fir, and western larch (*Larix occidentalis* Nutt.). Each puck contained 3 to 6 seeds, depending on species and management preference, and a total of 1,000 pucks were deployed across the project area.

Using heavy-lift UAV swarms, DroneSeed operators treated 51.3 acres (20.8 hectares) using up to three autonomously flown coordinated UAVs for each mission to achieve puck deployment. Operations were conducted immediately prior to, or during, snowfall events, leading pucks with dormant conifer seed to be buried under snow for the duration of winter. DroneSeed, along with the landowners, installed fixed radius plots and transects across the treated area to monitor dispersion pattern and germination/establishment rates. As of June 2020 (upon submission of this article), there was initial germination and rooting at some sites. The DroneSeed team will be reporting outcomes in future publications.

Conclusions

Aerial seeding and the supporting technology largely rely on dated technology (Becker 2001). DroneSeed has been working with stakeholders in the forestry and native plant restoration industries to develop products that address post-disturbance needs. Specifically, we have focused on the post-fire environment, where seedling production and response times are

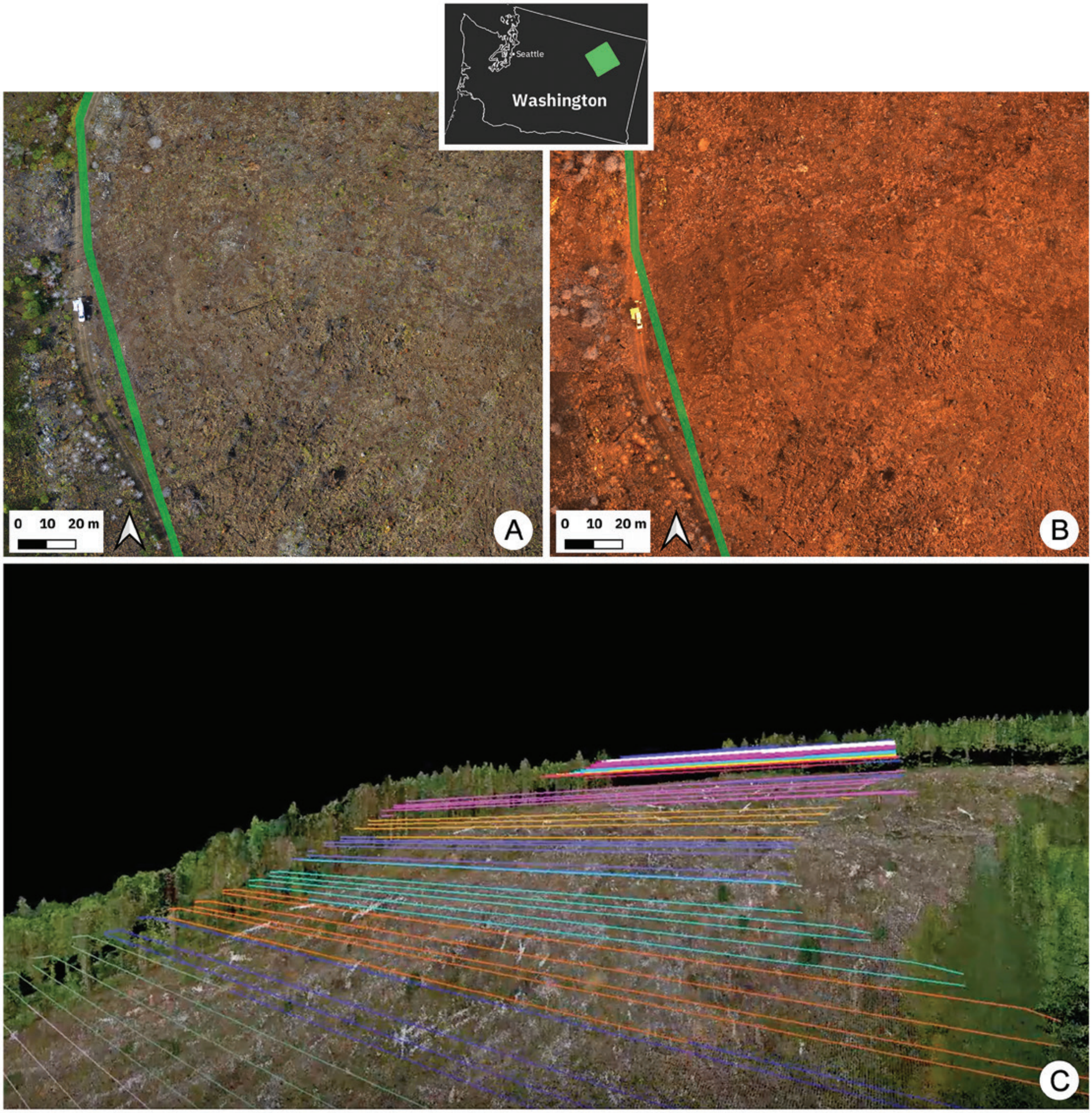

Figure 10. (a) RGB and (b) NIR imagery of a DroneSeed field site following drone survey operations. (c) Our survey process also collects LiDAR imagery, which is used to plan heavy-lift UAV operations designated by these overlaid multi-colored "mission lines." (Photos courtesy of DroneSeed 2019)

constrained by swift response needs and limitations within conventional reforestation supply chain and labor pools.

We offer improvement from broadcast payload applications— currently focused on seed. At the time of these projects, we were able to service up to 25 ac (10 ha) per day with a single team of four people and a three-aircraft drone fleet. The technical capacity for five aircraft in simultaneous flights exists; however, we are reviewing landing area protocols to safely achieve this by 2021 which should improve our daily acreage rate by 20 to 40 percent. These protocols are anticipated to lead to a daily service capacity of 200 ac (80 ha) per fleet by mid-2022. In the meantime, we are developing standard operating procedures for all UAV field operations, as they are a critical, and often overlooked, component of safe and scalable performance.

Seed "enablement" or "enhancement" strategies will continue to be a critical component of all machine-deployed seed, whether for aerial or ground-based applications. We anticipate monitoring academia and industry for improved materials and techniques, but also continuing fast throughput research, engineering, and manufacturing. Our primary goal is to improve seed-use efficiency and survival rates with each iteration of our technology and seed treatment processes. We currently focus on using non-improved, abundant seed sources, as improved genetic stock is often better suited for nursery investment. Our working species list is growing to include many economically important conifer species, a variety of rangeland grasses, and native plant species from across North America, Hawaii, and Oceania.

We do not see this technology as a replacement to conventional and time-tested regeneration strategies involving nursery stock production and manual planting operations. We anticipate developing this tool to assist with the growing backlog of reforestation and revegetation on private and public lands as a consequence of disturbance and initiatives to address climate change. In situations where native plant restoration is critical, landscapes prove challenging, and lag times in the conventional reforestation supply chain exist, seed distributed by UAVs may be opportune. Our puck can be stored in large quantities, much like raw seed, thus eliminating the economic risk of growing vast amounts of stock for unknown future use, and puck deployment can provide cost and safety advantages compared with hand-planting because each UAV can rapidly cover more terrain than manual planting.

Address correspondence to—

Matthew Aghai, DroneSeed Co, 1123 NW 51st Seattle, WA; phone: 425-659-3931 x 1007 email: matthew@droneseed.co

Acknowledgments

The authors thank Grant Canary (CEO and Founder) and the DroneSeed team for supporting the publication of our progress in this manuscript. The authors thank Russell Kramer, Trever Santora, Olga Kildisheva, and Diane Haase for content review and editorial assistance. The company thanks Dr. Gregory J. Ettl and the University of Washington for access to research sites in the United States, and our project partners Tmth-Spusmen Wilder and Shay Logue of the Colville Agency for their support in project development on the Colville Indian Reservation. The DroneSeed team is grateful for the support of Keith Mitchell, the Trident School Rugby Team, David Herries, John Barker, and Mark Dean and all the New Zealand landowners who provided support, access to trial sites, and assistance with data collection in 2019.

REFERENCES

Baena, S.; Boyd, D.S.; Moat, J. 2018. UAVs in pursuit of plant conservation – real world experiences. Ecological Informatics. 47: 2–9.

Barker, J.S.; Simard, S.W.; Jones, M.D. 2014. Clearcutting and high severity wildfire have comparable effects on growth of direct-seed interior Douglas-fir. Forest Ecology and Management. 331: 188–195.

Barnett, J.P. 2014. Direct seeding southern pines: development of techniques, use, and current status. Tree Planters' Notes. 57: 35–58.

Baumhauer, H.; Madsen, P.; Stanturf, J. 2005. Regeneration by direct seeding—a way to reduce costs of conversion. In: Stanturf, J.; Madsen, P. Restoration of Boreal and Temperate Forests. Boca Raton, FL: CRC Press: 349–354. Chapter 22.

Becker, R. 2001. Effective aerial reseeding methods: market search report. Gen. Tech. Rep. 01511204 –SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 19 p. https://www.fs.fed.us/t-d/pubs/pdf/01511204.pdf. (March 2020).

Belmonte, A.; Sankey, T.; Biederman, J.A.; Bradford, J.; Goetz, S.J.; Kolb, T.; Woolley, T. 2019. UAV-derived estimates of forest structure to inform ponderosa pine forest restoration. Remote Sensing in Ecology and Conservation. https://doi.org/10.1002/rse2.137. (March 2020).

Broadhurst, L.M; Jones, T.A.; Smith, F.S.; North, T; Guja, L. 2016. Maximizing seed resources for restoration in an uncertain future. Bioscience. 66(1): 73–79.

Campbell, T.E. 1981. Effects of endrin in repellent seed coatings on caged rodents. Vol. 174. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station.

Ceccon, E.; González, E.J.; Martorell, C. 2016. Is direct seeding a biologically viable strategy for restoring forest ecosystems? Evidences from a meta-analysis. Land Degradation & Development. 27(3): 511–520.

Commander, L.E.; Rokich, D.P.; Renton, M.; Dixon, K.W.; Merritt, D.J. 2013. Optimising seed broadcasting and greenstock planting for restoration in the Australian arid zone. Journal of Arid Environments. 88: 226–235.

Dumroese, R.K.; James, R.L.; Wenny, D.L.; Gilligan, C.J. 1988. Douglas-fir seed treatments: effects on seed germination and seedborne organisms. In: Landis, T.D. Proceedings, combined meeting of the Western Forest Nursery Associations. Western Forest Nursery Council, Forest Nursery Association of British Columbia, and Intermountain Forest Nursery Association: 155–160.

Duryea, M.L. 1987. Forest regeneration methods: natural regeneration, direct seeding and planting. Gainesville, FL: University of Florida, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. https://ufdcimages.uflib.ufl.edu/IR/00/00/18/15/00001/FR02400.pdf. (March 2020).

Engel, R.A.; Miriam, E.M.; Dennis, P.L. 2019. On the causes of the summer 2015 eastern Washington wildfires. Environmental Research Communications. 1(1): 1–10.

Erickson T.E.; Muñoz-Rojas, M.; Kildisheva, O.A.; Stokes, B.A.; White, S.A.; Heyes, J.L.; Dalziell, E.L.; Lewandrowski, W; James, J.J.; Madsen, M.D.; Turner, S.R.; Merritt, D.J. 2017 Benefits of adopting seed-based technologies for rehabilitation in the mining sector: a Pilbara perspective. Australian Journal of Botany. 65: 646–660.

Gornish, E.; Arnold, H.; Fehmi, J. 2019. Review of seed pelletizing strategies for arid land restoration. Restoration Ecology. 27(6): 1206–1211.

Groot, A. 1988. Methods for estimating seedbed receptivity and for predicting seedling stocking and density in broadcast seeding. Canadian Journal of Forest Research. 18: 1541–1549.

Grossnickle, S.C.; Ivetic, V. 2017. Direct seeding in reforestation—a field performance review. Reforesta. 4: 94–142.

Hallman, R.; Larson, J. E. 1980. Equipment for reforestation and timber stand improvement. Missoula, MT: Forest Service Equipment Development Center. 254 p.

Jalonen, R.; Valette, M.; Boshier, D.; Duminil, J; Thomas, E. 2018. Forest and landscape restoration severely constrained by a lack of attention to the quantity and quality of tree seed: insights from a global survey. Conservation Letters. 11(4): e12424.

Kemp, K.B.; Higuera, P.E.; Morgan, P. 2016. Fire legacies impact conifer regeneration across environmental gradients in the US northern Rockies. Landscape Ecology. 31(3): 619–636.

Kemp, K.B.; Higuera, P.E.; Morgan, P.; Abatzoglou, J.T. 2019. Climate will increasingly determine post-fire tree regeneration success in low-elevation forests, Northern Rockies, USA. Ecosphere. 10 (1): e02568.

Kildisheva, O.A. 2019. Improving the outcomes of seed-based restoration in cold and hot deserts: an investigation into seed dormancy, germination, and seed enhancement. Perth, Western Australia: University of Western Australia. 203 p. Ph.D. dissertation.

Kildisheva, O.A.; Dixon, K.W.; Silveira, F.A.; Chapman, T.; Di Sacco, A.; Mondoni, A.; Turner, S.R.; Cross, A.T. 2020. Dormancy and germination: making every seed count in restoration. Restoration Ecology. doi:10.1111/rec.13140. (June 2020).

Kruse, R.; Bend, E.; Bierzychudek, P. 2004. Native plant regeneration and introduction of non-natives following post-fire rehabilitation with straw mulch and barley seeding. Forest Ecology and Management. 196(2-3): 299–310.

Madsen, M.D.; Davies, K.W.; Boyd, C.S.; Kerby, J.D.; Svejcar, T.J. 2016. Emerging seed enhancement technologies for overcoming barriers to restoration. Restoration Ecology. 24: S77–S84.

Masarei, M.; Guzzomi, A.L.; Merritt, D.J.; Erickson, T.E. 2019. Factoring restoration practitioner perceptions into future design of mechanical direct seeders for native seeds. Restoration Ecology. 27(6): 1251–1262.

Merritt, D.J.; Dixon, K.W. 2011 Restoration seed banks—a matter of scale. Science. 332(6028): 424–425.

Montalvo, A.M.; Paul A.M.; Edith B.A. 2002. The relative importance of seeding method, soil ripping, and soil variables on seeding success. Restoration Ecology. 10(1): 52–67.

Nevill, P.G.; Tomlinson, S.; Elliott, C.P; Espeland, E.K.; Dixon, K.W; Merritt, D.J. 2016. Seed production areas for the global restoration challenge. Ecology and Evolution. 6(20): 7490–7497.

Palma, A.C.; Laurance, S.G. 2015. A review of the use of direct seeding and seedling plantings in restoration: what do we know and where should we go? Applied Vegetation Science. 18(4): 561–568.

Pearson, D.E.; Valliant, M.; Carlson, C.; Thelen, G.C.; Ortega, Y.K.; Orrock, J.L; Madsen, M.D. 2018. Spicing up restoration: can chili peppers improve restoration seeding by reducing seed predation? Restoration Ecology. 27(2): 254–260.

Pedrini, S.; Balestrazzi, A.; Madsen, M.D.; Bhalsing, K.; Hardegree, S.P.; Dixon, K.W.; Kildisheva, O.A. 2020. Seed enhancement: getting seeds restoration-ready. Restoration Ecology. Accepted author manuscript. doi:10.1111/rec.13184 (June 2020).

Peppin, D.; Fulé, P.Z.; Sieg, C.H.; Beyers, J.L.; Hunter, M.E. 2010. Post-wildfire seeding in forests of the Western United States: an evidence-based review. Forest Ecology and Management. 260(5): 573–586.

Pérez, D.R.; González, F.; Ceballos, C.; Oneto, M.E.; Aronson, J. 2019. Direct seeding and outplantings in drylands of Argentinean Patagonia: estimated costs, and prospects for large-scale restoration and rehabilitation. Restoration Ecology. 27(5): 1105–1116.

Porter, S.S. 2013. Adaptive divergence in seed color camouflage in contrasting soil environments. New Phytologist. 197(4): 1311–1320.

Sankey, T.; Donager, J.; McVay, J.; Sankey, J.B. 2017. UAV lidar and hyperspectral fusion for forest monitoring in the Southwestern USA. Remote Sensing of Environment. 195: 30–43.

Sankey, T.; Leonard, J.M.; Moore, M.M. 2019. Unmanned aerial vehicle-based rangeland monitoring: examining a century of vegetation changes. Rangeland Ecology & Management. 72(5): 858–863.

Scott, J.D. 1970. Direct seeding in Ontario. The Forestry Chronicle. 46(6): 453–457.

Seidl, R.; Rammer, W.; Spies, T.A. 2014. Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. Ecological Applications. 24(8): 2063–2077.

Seidl, R.; Rammer, W. 2017. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. Landscape Ecology. 32(7): 1485–1498.

Stephens, J.M.C; Molan, P.C.; Clarkson, B.D. 2005. A review of *Leptospermum scoparium* (Myrtaceae) in New Zealand. New Zealand Journal of Botany. 43(2): 431–449.

Stephens, S.L.; Burrows, N.; Buyantuyev, A.; Gray, R.W.; Keane, R.E.; Kubian, R.; Liu, S.; Seijo, F.; Shu, L.; Tolhurst, K.G; Van Wagtendonk, J.W. 2014. Temperate and boreal forest megafires: characteristics and challenges. Frontiers in Ecology and the Environment. 12(2): 115–122.

Stevens, R. 1999. Mechanical chaining and seeding. In: Monsen, S.B.; Stevens, R. Symposium Proceedings on Piñon-Juniper Habitats: Status and Management for Wildlife - 2016. Proceedings RMRS-P-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 281–284.

Sullivan, T.P. 1979. Repopulation of clear-cut habitat and conifer seed predation by deer mice. The Journal of Wildlife Management. 43(4): 861–871.

Taylor, J.B.; Kristina, L.C.; David, N.A.; Matthew, D.M.; Dean, E.P.; Samuel, B.S. 2020. Deterring rodent seed-predation using seed-coating technologies. Restoration Ecology. Accepted Author Manuscript. doi: 10.1111/rec.13158.

United States Department of Transportation (USDOT) Federal Aviation Administration. 2020.Unmanned aircraft systems (UAS) regulatory information. https://www.faa.gov/uas/ (March 2020).

Van Damme, L. 1988. Sowing method and seed treatment effects on jack pine direct seeding. 5(4): 237–240.