

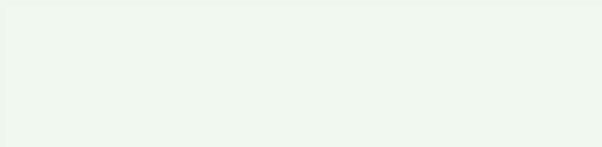
DNB311 – ID STUDIO 7: CAPSTONE

RESEARCH REPORT

**Exploring the effectiveness of
implementing autonomous technology
for seed dispersal to sustain & restore
biodiversity to degraded ecosystems**

Semester Two – 2025

Zane Li – Industrial Design



Executive summary

This report explores the question, “How might autonomous technology be effectively implemented by environmental initiatives in supporting seed dispersal to remote wilderness land regions experiencing biodiversity degradation?” This topic was considered to be important because natural seed dispersal is being disrupted by the increasing human activities. As described in the introduction and background section of the report, the decline of animal species that are responsible for seed dispersal impact many ecosystems’ ability to regenerate plant species. Benchmarking of existing autonomous solutions used for seed dispersal was also included in this report, where solutions were compared to identify market gaps. Two methods of research were used for this research project, the first being surveying of experts in ecology, conservation, autonomous technology and other related expertises. The second method involved reviewing archival observation videos demonstrating drone seeding experiments. After data collection, the report then goes through data analysis using a variety of methods.

The findings then revealed the most significant themes relevant to the research topic, the results were then discussed. As this research project is to inform a design solution, this report also included the most significant design implications. View each section of the report in detail below.

AI & Authenticity statement

AI Use statement:

I have utilised Generative AI in this report (ChatGPT) to assist ONLY in the following ways listed below: Correcting grammar and sentence structure, and inserting the correct punctuations. The way I have used AI was first write out my own text/paragraph in the best of my ability, then the text/paragraph that I have produced were copied and pasted into the prompt input of ChatGPT. I then requested Generative AI to review the text/paragraph that I have inserted, and repair any grammar and sentence structure, and to add or repair punctuations if necessary. However, it is noted that not ALL text/paragraph in this report have been repaired using Generative AI.

Your name: Zane Li

Date: 07/Sep/2025

Authenticity statement:

This is to certify that to the best of my knowledge, the content of this report is my own work. This report has not been submitted for any subject or for other purposes. I certify that the intellectual content of this report is the product of my own work and that all the assistance (Ex: research sources, benchmarked product information, observation videos, and benchmarked product images) received in preparing this report and sources have been acknowledged appropriately.

Your name: Zane Li

Date: 07/Sep/2025

Table of Contents

- Introduction	5
- Background	6
- Benchmarking	7
- Research	11
- Analysis & Findings	13
- Discussion	19
- Design implication	20
- Conclusion	20
- References	21
- Appendices	25

Introduction

One of the most precious values of our planet is that it is teeming with diverse types of plant and animal species. The extent of human activities in the era of accelerating climate change is increasingly threatening the natural processes responsible for sustaining healthy and rich ecosystems (Hernandez et al., 2023). Among these disrupted processes is seed dispersal, which plays a critical role in the repopulation of many plant species across regions (Tucker et al., 2021, Neuschulz et al., 2016). This, in turn, also supports animals by providing access to food sources (Mendes et al., 2024, Young et al., 2012). However, many of the animals responsible for seed dispersal are declining due to habitat fragmentation and other human-induced impacts (Mendes et al., 2024, Fontúrbel et al., 2015), leading to many connected ecosystems experiencing biodiversity decline (Artamendi et al., 2025).

While efforts have been made to support seed dispersal through human intervention (Rossander & Lideskog, 2024), its impact on remote wilderness regions suffering from declining biodiversity is limited (Robinson et al., 2022, Madsen et al., 2016). The increasing trend of autonomous technology across various sectors presents an opportunity for this project to explore its potential application in environmental efforts to reduce human impacts (Sharma et al., 2024, Mahant & Pal, 2025), which could help the project aim to bridge the gap between emerging technology and addressing environmental concerns. As such, this project proposes to investigate how autonomous technology might be effectively implemented by environmental initiatives in supporting seed dispersal to remote wilderness land regions experiencing biodiversity degradation. This moves the project toward a design-driven approach that contributes to long-term environmental goals (Ribeiro da Silva et al., 2015), including Goal 15: Life on Land, targeted by the United Nations, which focuses on protecting and restoring ecosystems (UN.ESCAP, 2022).

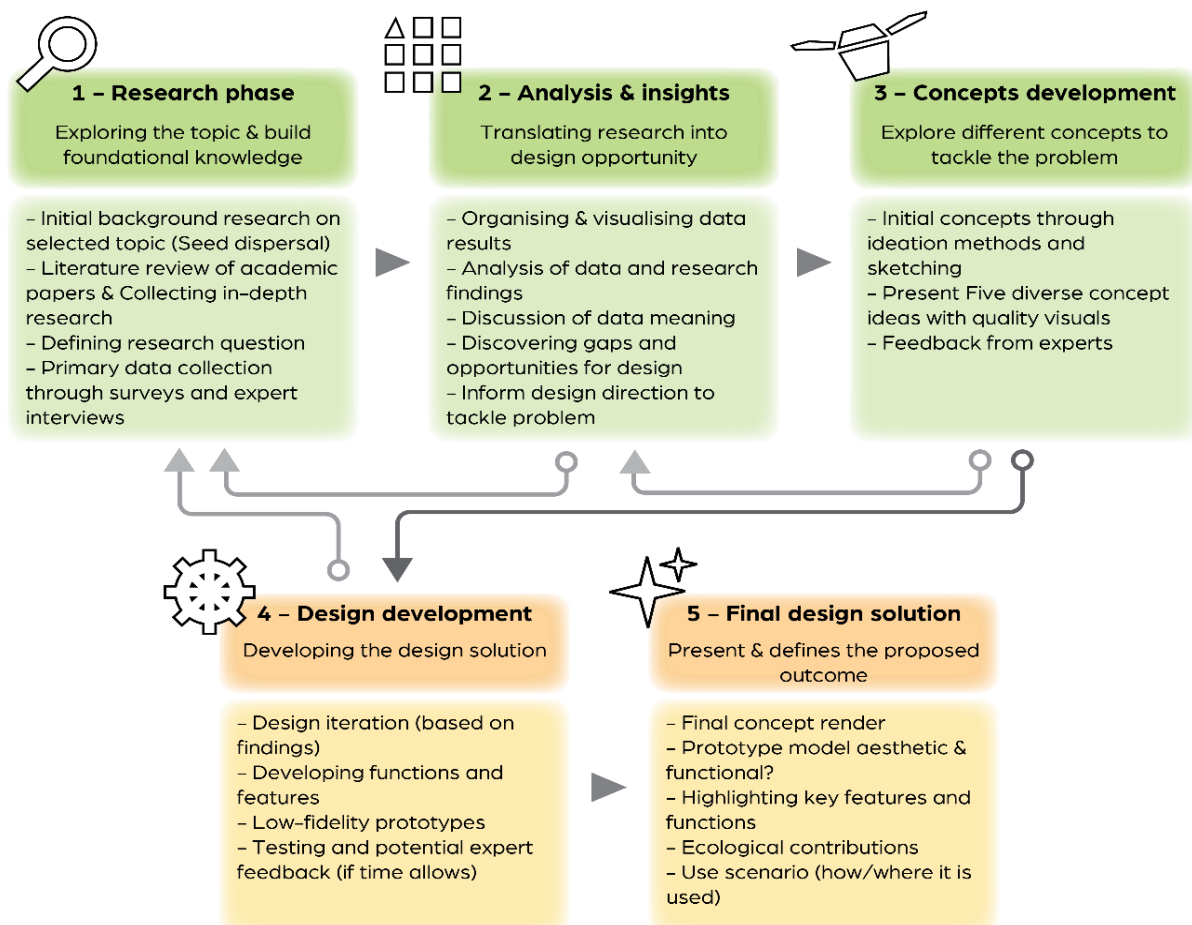


Figure 1: Visual representation of the initial planned project structure, with key stages being research, initial concepts development, and design development.

Background

Seed dispersal is a crucial area of study because it significantly contributes to global biodiversity, especially in a time where biodiversity loss is one of the most severe environmental challenges on the planet ([Beckman & Sullivan, 2023](#)). Seed dispersal is the natural distribution of seeds to other wilderness regions, enabling the recruitment of plant species to enrich ecosystems ([Fontúrbel et al., 2015](#)). Additionally, an indirect outcome of seed dispersal is providing food sources for the many animals that depend on it, attracting diverse wildlife and enhancing overall biodiversity ([Bonfim et al., 2018](#)). Seed dispersal occurs through biotic or abiotic means, while water and wind naturally carry seeds across landscapes, a significant proportion of seed dispersal relies on animals ([Hernandez et al., 2023](#)), as mentioned previously. This mutualistic relationship means the process continues as animals help with seed movement through their natural behaviours ([Teixido et al., 2022](#)). Anthropogenic activities, which in this case refer to human impacts in the form of deforestation, land-use, hunting and promoting climate change ([Fricke et al., 2025](#), [Sperry et al., 2021](#)), contribute to the decline of animal seed dispersers ([Sampaio et al., 2021](#), [Bofim et al., 2018](#)). As a result, the consequences of reduced seed dispersal activity have reached even distant regions untouched by anthropogenic activity, leading to large-scale ecological imbalance ([Young, 2012](#)).

Understanding how ecological interactions between species are impacted by anthropogenic activity will be important for preservation efforts ([Bomfim et al., 2018](#)). The clearing of native fruit-bearing plants not only reduces the availability and diversity of food resources but also fragments habitats, dividing them into patches of various sizes ([Cazetta & Fahrig, 2021](#), [Bomfim et al., 2018](#)). While studies suggest that some frugivorous birds, particularly smaller-sized, can persist in these degraded environments ([Ong et al., 2021](#)), birds with larger body mass are especially sensitive to habitat loss as they struggle to meet their metabolic demands ([Mendes et al., 2024](#), [Godínez-Alvarez et al., 2020](#)). Larger birds are considered priority seed dispersers due to their capacity to consume greater quantities of fruit and disperse larger seed types ([Godínez-Alvarez et al., 2020](#), [Vidal et al., 2013](#)). Therefore, it has been suggested that their decline diminishes both the quality and quantity of seeds being dispersed ([Sperry et al., 2024](#), [Ong et al., 2021](#)). Moreover, these species are responsible for long-distance dispersal, which benefits remote ecosystems by migrating across extensive distances and assists in sustaining biodiversity ([Lososová et al., 2023](#), [Neuschulz et al., 2016](#)).

The science of natural seed dispersal has established that it is a fragile process vulnerable to disruption from anthropogenic activities ([Mendes et al., 2024](#), [Fricke et al., 2025](#)). The fact that numerous plant and animal species depend on seed dispersal for regeneration and survival makes it incredibly crucial for maintaining the health of ecosystems. Background research highlights the importance of preserving seed dispersal processes, however it can be predicted that this would be challenging with the trend of growing population, which only drives more land-use for urbanisation and resource consumption ([Jakovac et al., 2021](#)).

Benchmarking

The growing recognition of biodiversity decline has accelerated the development of autonomous devices designed to reverse ecological damage. Their application is valued largely due to their ability to perform tasks beyond human capabilities (Robinson et al., 2022). Benchmarking prominent existing solutions provides an understanding and comparison of their strengths and limitations, while also offering insight into the existing technological progress and revealing significant gaps and opportunities for further innovation.

Autonomous technology used for restoring biodiversity focuses on re-establishing plant populations in degraded ecosystems. Five most prominent and recent solutions were identified (Table 1 below), each having its unique method of seed dispersal and relative measure of success. Aerial drones are the most widely adopted approach, valued for their ability to cover large areas with speed (Sharma et al., 2024). The DJI Agras T100 is a recent flagship model primarily designed for agricultural spraying (NuWay Ag, 2025, DJI, n.d.), but also adaptable for ecological restoration. In contrast, the Airseed Artemis drone was specifically developed for ecological restoration (Rees, 2022). It was designed to release seed pods composed of mineral materials that encapsulate a seed (AirSeed, n.d., Rees, 2022).

Robotic devices are of significant interest for their ability to perform complex functions on the ground, which are beyond the capabilities of drones. The A'seedbot is a final year student project that demonstrates a miniature device capable of roaming around light terrain and selecting optimal sites for dispersal (Sheth, 2021). While it's a prototype, it represents an innovative design direction. The LandLife Tree Seeding Robot represents a more advanced engineered solution. Developed in 2021 by LandLife and Continental Engineering Service, it is capable of traversing rough terrains and planting seeds into the soil (LandLife, n.d.). Lastly, the FarmDroid FD20 was developed specifically for large-scale agricultural seed planting (FarmDroid, n.d.). It demonstrates strong potential for ecological restoration and is therefore included for benchmarking.

Table 1: Summary of existing autonomous solutions selected for benchmarking.

					
MODEL	DJI Agras T100	AirSeed Artemis	A'seedbot Prototype	LandLife Tree Seeding Robot	FarmDroid FD20
YEAR	2025	2021	2021	2024	2020
Development	– Developed by global drone industry leader DJI	– Developed by private environmental restoration company Airseed	– Final year student project by Mazyar Etehad from the Dubai Institute of Design and Innovation	– Developed by private environmental restoration company LandLife in collaboration with Continental Engineering Services	– Developed by agricultural robotics company FarmDroid
Primary context	Agricultural purposes	Reforestation	Transforming desert environments	Reforestation	Agricultural planting
Seed dispersal function	Moves in the air and scatter seeds at a controlled rate to the terrain below	Moves in the air and drops seed pods precisely to the desired position	Roam around the desert terrain and push seed into the ground to increase germination success	Can move on rough terrain, plants seed by drilling into the soil and patching it up	Move on flat fields, can carry out planting of multiple seeds by sowing and placing them in optimal depth
Distinguished features	Capable of adjusting seed dispersal rate, also equipped by water and pesticide sprayer	Seed pods contain mineral materials that protects the seed, it also breaks down to help the seed germinate	Solar powered device that can survey the area to determine optimal seed placement area	Creates a patch in the ground for water collection, drills the optimal depth and shoots the seed into the soil	Solar powered device, also capable of clearing weeds to make room for seed growth

LEGEND:

DJI AGRAS T100



AirSeed Artemis Drone



A seedbot Prototype



LandLife Tree Seeding Robot



FarmDroid FD20

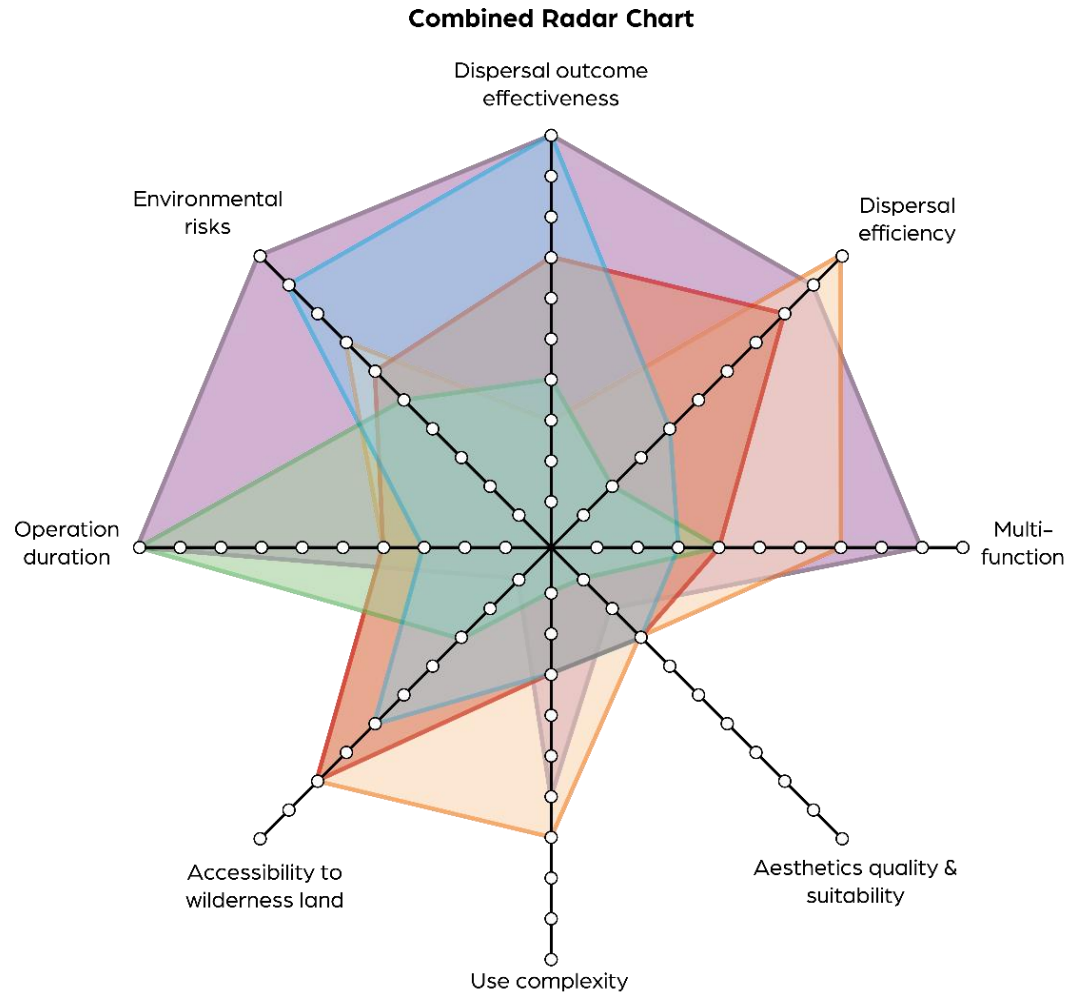


Figure 2: Combined radar chart illustrating the performance of the five benchmarked solutions in the eight crucial variables using colour patches, highlighting individual strengths and weaknesses on a 1 to 10 scale, with 10 being highest rated score, and 1 being lowest rated score.

Eight key variables were identified as most relevant for assessing the performance of autonomous devices used for seed dispersal to restore biodiversity, as represented in Figure 2 above. Dispersal effectiveness, which refers to the ability to produce successful germination outcomes, is arguably the most significant variable. Figure 2 illustrates that the LandLife robot and FD20, which are robotics capable of precision seed planting, significantly outperform drones by creating favourable conditions for seed germination ([Lamichhane et al., 2018](#)). The Agras T100 is considered to have poor effectiveness because it relies on scattering high volumes of raw seeds with limited germination success ([Castro et al., 2022](#), [Sharma et al., 2024](#), [Stamatopoulos et al., 2024](#)). However, figure 2 further illustrates that drones demonstrate superior efficiency by being able to disperse across large areas quickly ([Robinson et al., 2022](#), [Rossander & Lideskog, 2024](#)). This reveals a market gap for solutions that combine aerial mobility efficiency with the effectiveness of precision planting.

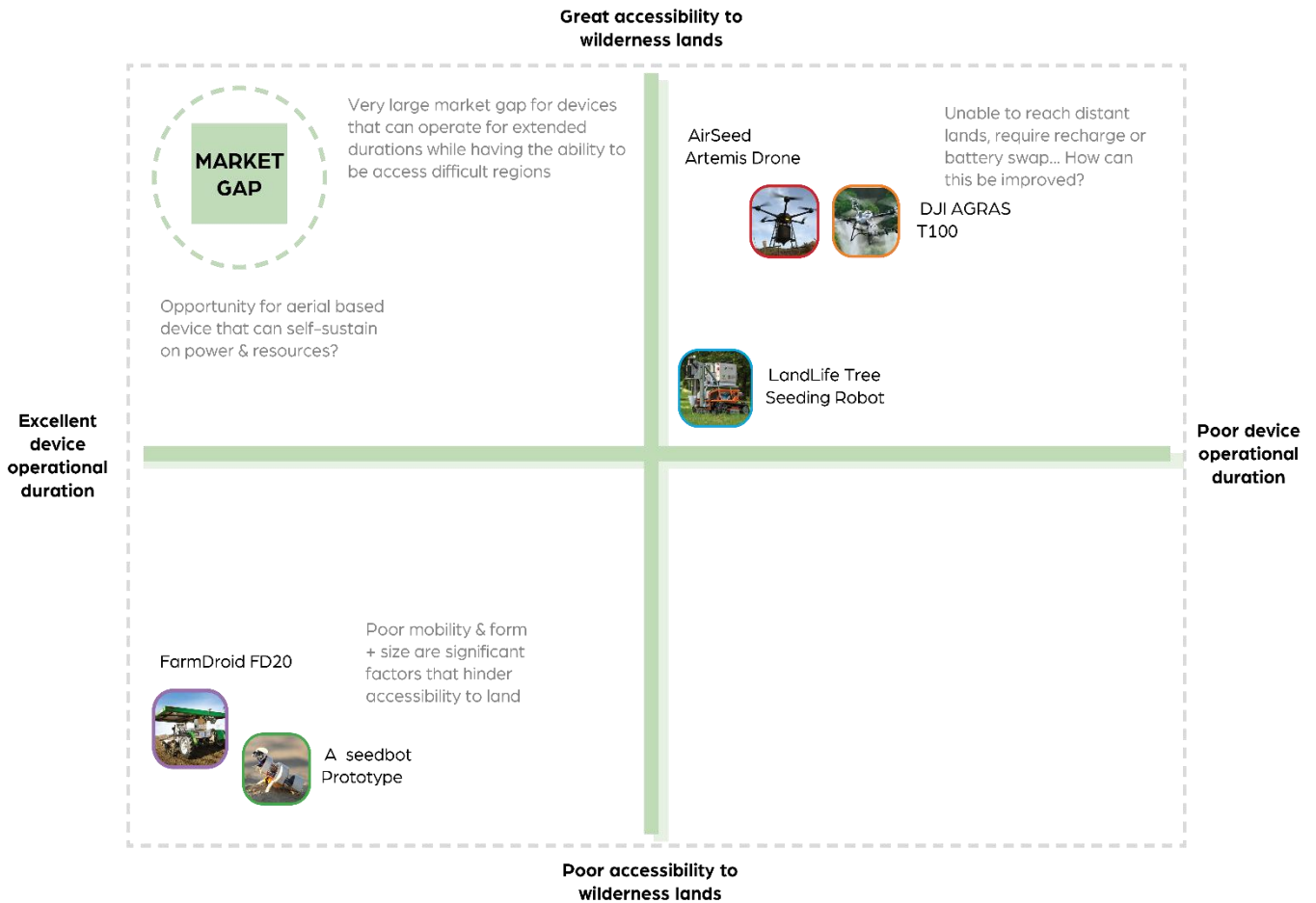


Figure 3: Matrix graph illustrating the performance of each benchmarked solution based on their individual ability to access lands (Y-axis) and operational duration (X-axis). The position of the identified market gaps is highlighted.

Access to wilderness lands is recognised as a significant limitation, especially for ground-based robotics. Figure 2 above illustrates that while the FD20 excels in effectiveness and efficiency, it has the poorest land access capability, because its large size makes it unsuitable for natural environments with dense vegetation. Comparatively, the LandLife robot scored higher as its design focuses on adapting to different terrains to reach more lands (LandLife, n.d., Hekkert, 2024), though it remains limited when compared to the aerial mobility of drones. However, drones are constrained by high energy consumption and dependence on manual recharging (Sharma et al., 2024, Stamatopoulos et al., 2024), which prevents them from reaching distant areas. In contrast, the FD20 and A'seedbot possess superior endurance by relying on solar self-sufficiency (Sheth, 2021, FarmDroid, n.d.).

Based on Figure 2, a correlation between the two variables can be suggested, where devices with greater land access often have shorter operating times. This relationship is further visualised in Figure 3 above, where it demonstrates that solar-powered devices with superior operational duration, but poor land accessibility, are positioned in the lower-left quadrant. While drones, offering greater land accessibility but shorter duration, appear in the upper-right. Notably, no device occupies the upper-left quadrant, which represents optimal conditions in both variables. This absence suggested a significant market gap for autonomous devices with excellent accessibility to land while sustaining longer operations with minimal human assistance.

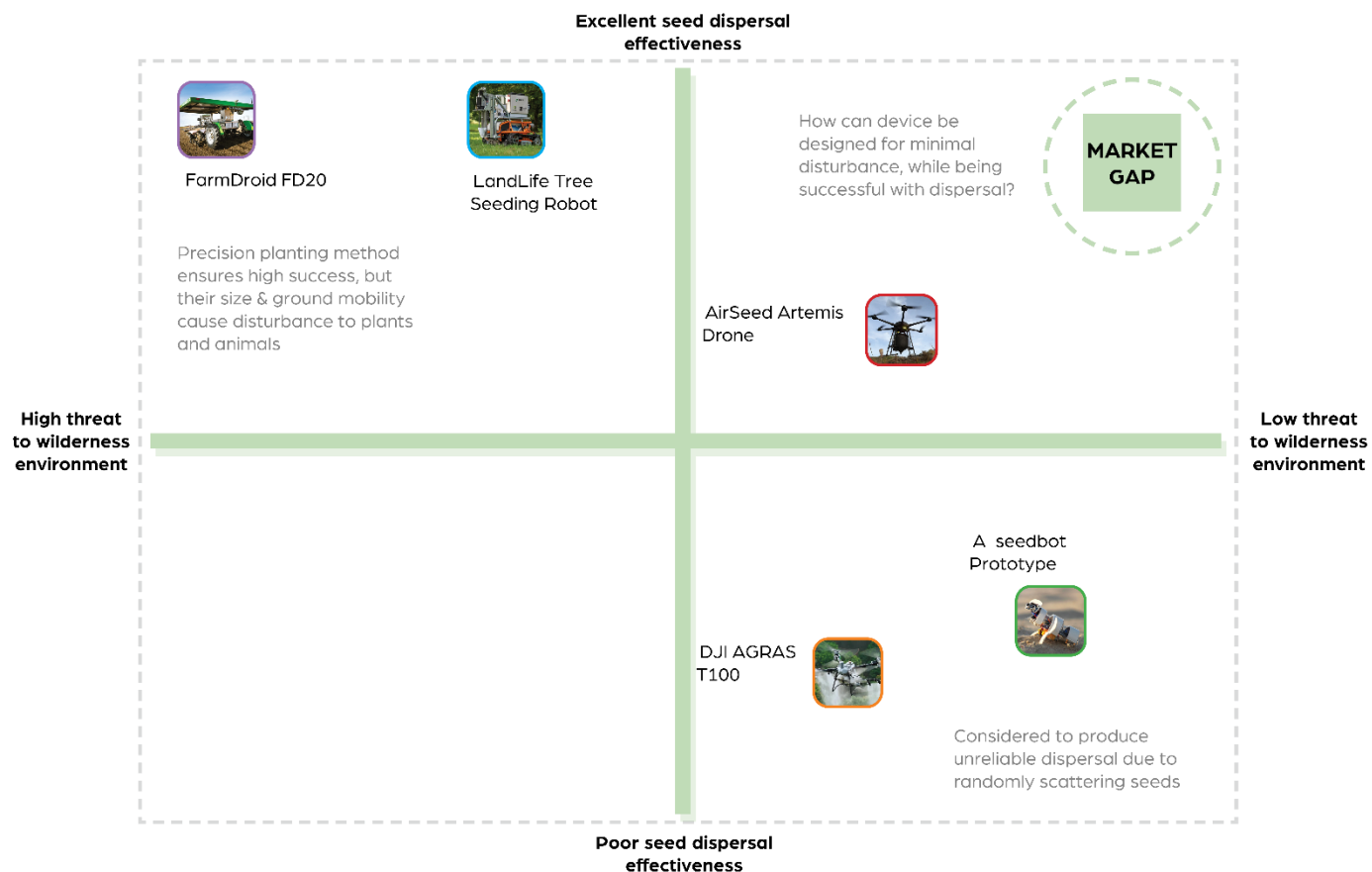


Figure 4: Matrix graph illustrating the performance of each benchmarked solution based on their individual seed dispersal effectiveness (Y-axis) and risk to the environment (X-axis). The position of the identified market gaps is highlighted.

Figure 4 illustrates another significant correlation between dispersal effectiveness and degree of environmental risk. Ground mobility devices like the LandLife robot, which relies on heavy-duty tracks that can potentially damage small plants ([Continental Engineering Services, 2024](#)), are considered to pose higher environmental risks. Therefore, it is positioned at the very top of the upper-left quadrant in Figure 4, suggesting that robotic devices with the greatest effectiveness also pose greater threats to the environment. Notably, no device occupies the upper-right quadrant, which represents high effectiveness with minimal environmental impact. This suggested a strong market gap for solutions that balance both outcomes.

Benchmarking the five diverse autonomous seed dispersal solutions revealed major opportunities for innovations that target effectiveness, efficiency, low environmental risk, operational duration and accessibility to land.

Research

The approach for this research project was to utilise both primary and secondary data collection, which supports triangulation by allowing findings to be corroborated and establishing connections. The research question involves exploring the effectiveness of autonomous technology for seed dispersal in degraded wilderness environments experiencing biodiversity decline. Therefore, data collection targeted key themes that would help with gaining scientific and technical understanding.

Primary data collection was conducted through distributing surveys to experts in fields related to the research question. Given the highly scientific nature of the topic, the decision to focus on targeting experts was deliberate, as it was anticipated that individuals with extensive knowledge and experience have the best capacity to provide informed and reliable responses. The majority of experts invited were academic professors, researchers, and scientists specialising in ecology, environmental science, and restoration applications. This was to ensure the data collected would support a strong understanding of ecological context and themes. Although it was recognised that many of these experts may have limited familiarity with autonomous technology, their perspectives were beneficial for understanding the ecological and practical requirements that such technology should address. To complement this, a smaller number of experts in autonomous technology and robotics were also invited to incorporate technical perspectives to enrich the data.

Surveys were selected for this research project due to their advantage of gathering structured information from multiple experts efficiently. Close-ended questions in the form of multiple choice and interval rating enabled the identification of general trends, most notably to gain insight into which ecological contexts would most benefit from technology-assisted seed dispersal and the attitude towards autonomous technology for ecological restoration. The open-ended questions were valued as they provided the opportunity for detailed textual responses comparable to those obtained in structured interviews. It allowed experts to further elaborate on ecological risks, potential applications, and contexts where autonomous technology might be most effective. Additionally, it also encouraged personalised responses based on individual experience, potentially bringing attention to new areas of exploration. The complexity of the topic meant the survey was relatively extensive, as such, questions were carefully framed in accessible language, avoiding complex technical terminology that might appear foreign.

The survey was distributed electronically to maximise reach and convenience. 48 experts were carefully selected for participation based on their specialities highlighted by their publicly available professional profiles on university and NGO websites. This purposive selection strategy ensured that the data collected rested on an expert-driven foundation, which strengthened the integrity and reliability of the findings.

Secondary research data was obtained through reviewing archival observation videos, which were publicly available online sources documenting drone dispersal experiments. This method was selected for its capacity to provide video and audio data evidence based on the direct demonstration of autonomous technology in operation. Unlike purely textual data, videos have the advantage of representing technical processes with visuals. Archival observations were also valued for revealing limitations and gaps based on real-world practices, to provide understandings that may not yet be extensively addressed in survey data or academic literature.

Drone dispersal was the focus for observation because it represents the most widely adopted method of autonomous seed dispersal, which meant there was an abundance of video sources available for selection. To ensure source integrity, experiments in two of the three selected sources were conducted by university research institutions. The first documented the dispersal of native prairie seeds under harsh snowy weather to restore a degraded landscape, providing insight into performance and environmental adaptability. The second demonstrated the structured process of large-scale dispersal on farmland. Although not directly focused on ecological restoration, it provided valuable technical understanding of how drone dispersal operates in practice. Lastly, the third source was produced by a professional practitioner, providing a detailed walkthrough of the process. While this video was argued to have less academic integrity, it was particularly valuable for highlighting technical challenges absent in institutional experiments. The evidence was also corroborated with university-produced sources, thus strengthening its relevance.

Visual and audio data were collected through thorough observation of selected archival sources. Relevant photographic stills were captured as screenshots, while complete audio transcripts were generated using the AI software TurboScribe, which was identified after multiple trials as the most accurate tool. Despite this, manual refinements were required to address several inaccuracies and to include verbal reactions and pauses that the software excluded, as these were considered important for capturing emotional nuance and meaning. Together, these two forms of data were very valuable as they allowed both observable processes and expert explanations to be collected.

Research was conducted using a combination of primary and secondary data collection methods. Surveying enabled the collection of quantifiable data to identify broader trends, while also capturing expert perspectives. Archival video observations offered practical demonstrations of technology in operation. Together, this helped the research to effectively explore the scientific and technical aspects of the topic.

Analysis & Findings

The conclusion of data collection progresses the research into analysis. Survey responses from experts were examined alongside coded information from archival observation videos to extract results most relevant to the research question. Analyses were conducted using methods that enabled comparisons of results and the identification of themes, with figures and tables used to illustrate results and highlight relevant findings.

Multivariate analysis was conducted for relevant survey data to examine relationships between categorical and numerical variables. This method allowed trends and associations to be identified across expert responses, particularly considering a significant proportion of the data were categorical and interval in nature. For open-ended textual responses, conceptual analysis was applied. Responses were coded with relevant themes, and their frequency was assessed to identify key concepts, problems, and opportunities repeatedly highlighted by experts. This method also allowed distinctive themes to be recognised from individual responses, which may not be frequently represented in the data, but ensured the inclusion of unique perspectives.

In analysing the observation videos, affinity diagramming was used. Raw visual and audio data were coded with themes and then systematically assigned and organised into diagrams that categorise the data. This method enabled connections to be drawn across technical demonstrations of drone dispersal, which was useful in highlighting important variables, recurring challenges and practical limitations that are more relevant to the technical aspect of autonomous technology.

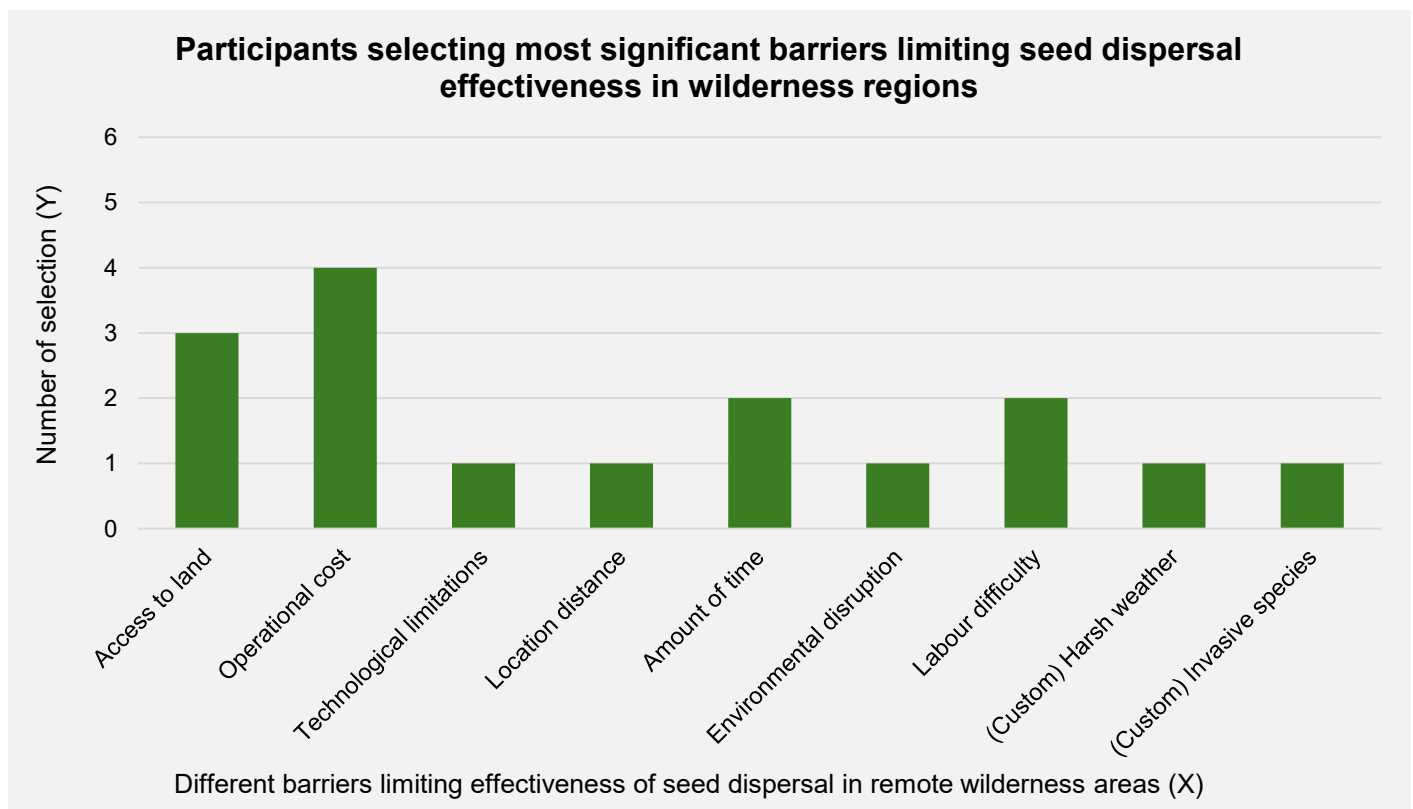


Figure 5: Bar graph comparing the number of selections (X-axis) of each barrier limiting seed dispersal effectiveness in wilderness regions (Y-axis). Individual expert participants were requested to select three aspects from a predefined list that they considered to be most significant. The option to select a custom response was provided to allow participants to input alternative barriers not captured within the list.

One of the most significant findings emerged from categorical data representing the significant barriers limiting seed dispersal effectiveness in wilderness regions. The results of multivariate analysis are illustrated in Figure 5 above. It can be described that the majority of experts, 4 out of 6, or 66.7% have recognised operational cost as one of the three most significant barriers. This was closely followed by land accessibility, selected by three or 50% of experts. Labour difficulty and time each received two selections, while the remaining five barriers only carried one selection. Although findings indicated that operational cost and land accessibility emerged as the barriers with the strongest influence on limiting effectiveness, the distribution of selection suggested that all barriers hold some relevance, given that all were selected at least once. Therefore, it can be argued that prioritising focus to address the leading two factors may yield the greatest improvements in practice.

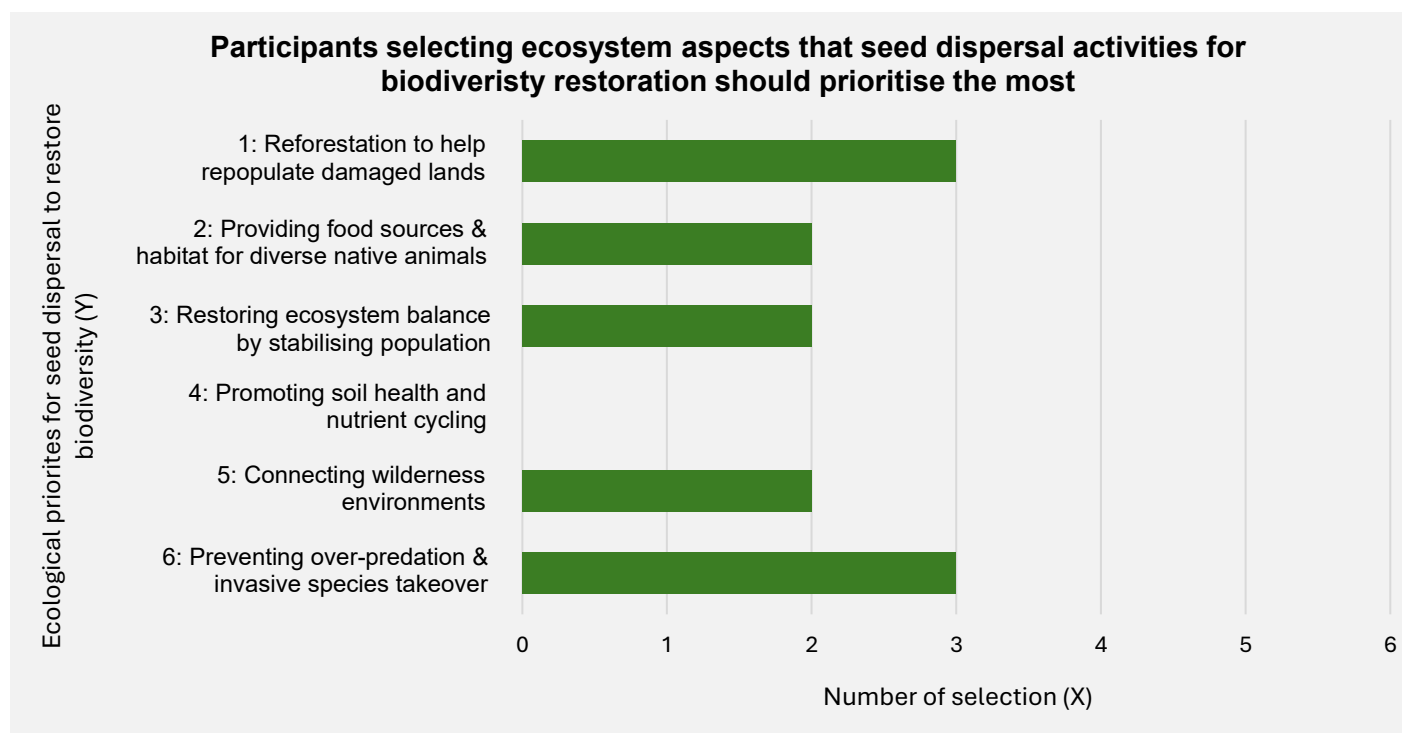


Figure 6: Bar graph comparing the number of selections (X-axis) of each ecological aspect (Y-axis). Individual expert participants were requested to select two aspects from a predefined list that they considered to be the priority for seed dispersal activities in supporting biodiversity restoration.

Figure 6 illustrates that the most frequently selected aspects were reforestation to repopulate damaged lands and preventing over-predation and invasive species takeover. Each received three selections, representing 50% of experts. This strongly emphasises that seed dispersal efforts should prioritise plant regeneration and address ecological threats that hinder it. Providing food sources for native animals, stabilising populations, and connecting wilderness environments, each received two selections, indicating a moderate level of prioritisation for these aspects. Notably, promoting soil health received no selections, suggesting it was perceived as a secondary objective with lesser significance for biodiversity restoration.

When referring to previous data in Figure 5, it was revealed that one custom response identified invasive species as a significant barrier to seed dispersal. A connection can be established with findings shown in Figure 6, where preventing the takeover of invasive species emerged as one of the top priorities for biodiversity restoration. The recurrence of this theme across datasets suggested a consistent trend of experts recognising the disruptive role of invasive species in impacting the effectiveness of seed dispersal activities.

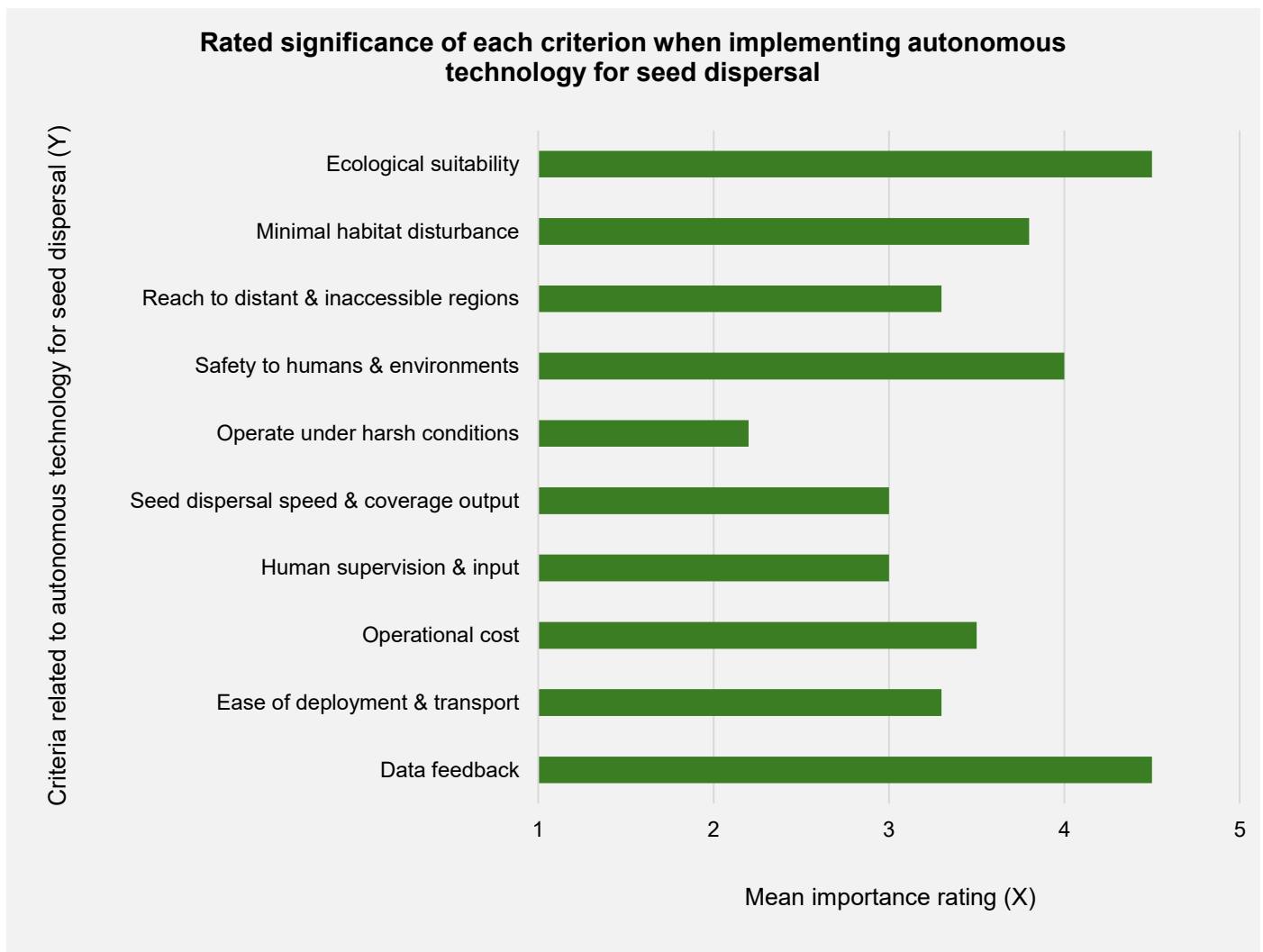


Figure 7: Bar graph comparing the mean importance rating (X-axis) of each criterion when it comes to implementing autonomous technology for seed dispersal in wilderness regions (Y-axis). Ratings were based on a scale where 1 = least important, and 5 = most important.

Figure 7 above illustrates the multivariate analysis of interval data representing the rated importance of each criterion when applying autonomous technology for seed dispersal. Given the wide distribution of ratings across the scale, as presented in the original data (See appendices 17 to 26 below), the mean value was adopted as the primary measure. Results revealed that ecological suitability and data feedback were rated highest, sharing a mean value of 4.5. Safety was also rated notably high with a mean value of 4.0, followed by minimal habitat disturbance with a rating of 3.8. Other criteria clustered within a mid-range of 3 to 3.5, apart from operating under harsh conditions, which stood out with the lowest mean rating of 2.2, indicating less importance relative to other criteria. The findings suggested that ecological adaptability and the ability for autonomous operations to provide data feedback are considered by experts to be dominant considerations over purely technical performance.

Table 2: Frequency of relevant key themes to the research topic identified in the conceptual analysis of relevant textual short responses data from expert survey participants.

Theme	Frequency	Data example - Quote
Ecological risks & unintended impacts	6	"Creating novel ecosystems that perform worse than the original ones"
Seed selection & placement	5	"Putting the right seed in the right place"
Cost barrier	4	"At the moment it's very expensive"
Restoration complexity	4	"Need to disperse a community of plant species, not just monoculture"
Monitoring & feedback	3	"Need to be able to monitor output and ongoing germination"
Post-dispersal maintenance	3	"Most seeds won't survive without follow-up maintenance (e.g., watering)"
Potential hazards	2	"An ecological risk could be fires from batteries or tech waste"

The result of conceptual analysis applied to textual data is represented in Table 2 above. Eight key themes emerged across three datasets of short responses that were most relevant to the research question (See appendices 27, 32 and 33 below). Ecological risks emerged as the most frequent theme across six responses. When experts were asked to identify risks or unintended impacts, one expert suggested "creating novel ecosystems that perform worse than the original ones", while another noted "loss of ecosystem processes involving natural seed dispersers". These responses highlighted the ecological concerns of inappropriate autonomous technology implementation. The theme of seed selection and placement also appeared prominently, identified in five responses that highlighted the importance of matching seeds to their environment. This was expressed in quotes like "putting the right seed in the right place" and concerns like "wrong plant in the wrong place".

Cost barrier emerged in four responses, with simple and direct statements like "cost of systems" and the technology is "at the moment it's very expensive". Furthermore, the theme of restoration complexity was also addressed in four responses, with notable responses stressing the need to "dispersing a community of plant species, not just monoculture of one species". This suggests that autonomous solutions should prioritise meeting ecological criteria to produce effective outcomes instead of simply focusing on successfully dispersing seeds.

Table 3: Summary of categories, themes, and tagged concepts derived from the affinity diagram (See appendix 36 below for link) of coded visual and audio data from three observational video sources.

Category	Theme	Tagged concepts
Operational workflow	Pre-dispersal activity	Pre-dispersal activity, Adding material, Calibration, Device deployment, Seed material adaptability, Landing condition, Dispersal mapping; Decreased productivity
	Dispersal process	Autonomous operation, Software assist, Remote controlled, Manual input, Custom setting, Supervision, Aerial spreading, Large-scale dispersal, Seed scattering, Random scattering, Desired patterns; Successful scatter, Unpredictable, Obstacles on-site
	Operational complexity	Operational complexity, Spread calibration, Technical issue, Decreased productivity, Wasted material, Improvised solution, Sustainability, Unsustainable, Additional equipment
Human factors	Human dependence	Human reliance, Supervision, Remote controlled, Manual input, Custom setting, Additional equipment, Frequent maintenance, Cleaning difficulty, Removing material, Repetitive labour, Device deployment; Improvised solution; Decreased productivity
	Human workload	Effort-demanding; Exhausting labour; Repetitive labour; Uncomfortable labour; Improvised solution; Design flaw; Decreased productivity
	Ergonomics considerations	Exhausting labour; Uncomfortable labour; Carrying feature; Convenience; Transport difficulty, Cleaning difficulty; Removing material; Ease of use; Adding material; Design flaw
	Training & Expertise	Technical knowledge; Improvised solution; Experience; Human error
Autonomous device design	Structure & protection	Exposed hardware, Fragile parts, Non-collapsible, Collapsible feature, Hatch design, Vulnerable design, Mechanical assembly, Large size
	Dispersal function	Design flaw, Component customisation, Dispersal tool, Aerial spreading, Material selection, Seed flow problem, Hatch design, Seed material adaptability, Remote controlled, Manual input
	Operational risks	Safety, Design flaw, Human risks, Dangerous, Propeller risks, Human reliance
	Device maintenance	Human reliance, Recharge method, Energy priority, Adding material, Component customisation, Cleaning difficulty, Removing material, Frequent maintenance, Accelerate process, Wasted material, Additional equipment, Mechanical assembly, Design flaw
	Interaction design	Interaction design, Simplicity, Simplistic interaction, Ease of use, User-experience, Simplistic visual, Physical UI design, Digital UI design, Adjustable camera, Hatch design, Device deployment, Transport difficulty, Remote controlled, Complex visuals, Non-collapsible
	Feedback & response	Active feedback, Indication, Device response, Supervision
Device performance	Dispersal effectiveness	Effective dispersal, Efficiency, Desired patterns, Successful scatter; Random scattering, Unreliable dispersal, Unpredictable
	Adaptability	Seed material adaptability, Environmental capability, Lifting power, Material capacity, Harsh weather
	Coverage & reach	Land coverage, Large-scale dispersal, Aerial spreading, Custom setting, Component customisation, Dispersal tool, Efficiency
	Reliability	Unreliable, Design flaw, Technical issue, Device response, Seed material adaptability; Decreased productivity; Seed flow problem
	Autonomy condition	Autonomous operation; Software assist, Remote controlled; Manual input; Custom setting, Supervision, Human reliance
Environment context	Environmental conditions	Suitable land, Landing condition, Environmental condition, Harsh weather, Degraded land, Weed problems, Obstacles on-site, Large-scale dispersal
	Accessibility	Transport difficulty, Device deployment, Large size, Additional equipment, Landing condition, Energy priority
	Potential disturbance	Noise produced; Landing method; Landing condition; Large size
Emotional response	Task response	Positive expectation, Exhausting labour, Uncomfortable labour, Frustrated, Carefulness, Accelerate process
	Risk perception	Cautious, Concerned, Experience, Carefulness
	Perceived complexity	Experience, Confusing, Cautious, Improvised solution

Data analyses conducted through affinity diagramming identified three key recurring themes most relevant to the research question. As shown in Table 3 above, operational complexity emerged as a significant theme, as all three observation sources demonstrated the number of processes and requirements that complicate drone dispersal operations. A key observation was the extent of essential activities done manually prior to dispersal action. Visual stills in video one (4:01) and video three (12:12) demonstrated the controller screen displaying a mapped dispersal field, which operators created manually by adding boundaries. Device configuration further contributes to complexity, particularly highlighted in video two at 2:56, showing the operator manually adjusting settings including hopper outlet size and spin speed, on the remote. This burden is reinforced by the accompanying quote at 2:53 stating “What do you choose? Well the faster you spin it, the wider you should throw it, but of course you might damage seed”, suggesting the complication of knowing how to configure the device to perform as desired.

Reliability emerged as a recurring theme across data. Concepts like unreliable dispersal and decreased productivity (Table 3 above) were frequently tagged. One significant instance of unreliability was highlighted in video one, where the technology struggled to adapt to different seed materials. As the professional addressed at 4:46, “The next issue we really ran into was... the seed flow. Uh that real fluffy seed... we mixed all the seeds together, tried to give it a way to flow a little bit better. There was so much chaff, and yet it just still couldn’t really go through”. It would be relevant to address technological limitations that impact the reliability of the device in ensuring desired seed dispersal outcomes.

Human dependence was recognised as a significant central theme. Despite data demonstrating evidence of autonomous dispersal, a substantial amount of manual input was required. As shown in Table 3, concepts associated with human labour at varying difficulties were frequently tagged. Repetitive labour was particularly observed in video one at 3:22, where seed material was repeatedly transferred from a bucket to the drone each time it emptied. Video two documented another instance at 16:07, where the battery was manually replaced after each trip across the field. Exhausting labour was also identified multiple times, most notably in video two at 7:01, where the operator constructed an improvised platform using buckets to elevate the drone, followed by 8:00 where the operator tediously dug into the ground beneath the drone to place a bucket for calibration. It can be suggested that autonomous drone dispersal remains heavily reliant on human intervention.

Overall, multivariate and conceptual analysis of survey data primarily focused on identifying ecologically related themes that are important to consider for the research. While the analysis of archival video observation data through affinity diagramming prioritised themes with strong technological contexts.

Discussion

The findings generally establish that the effectiveness of autonomous technology for seed dispersal to restore biodiversity is strongly limited by both ecological and technological variables. Experts prioritised the ecological adaptability of autonomous solutions and their ability to provide data feedback (Figure 7). This aligns with background literature that addressed the importance of matching different seeds to their ideal site conditions and monitoring their ongoing post-dispersal status once released to the environment ([Lamichhane et al., 2018](#), [Sharma et al., 2024](#), [Doherty et al., 2017](#)). This supports the view that germination success must be verified, instead of assuming success from dispersal alone ([Doherty et al., 2017](#), [Kildisheva et al., 2020](#)). Furthermore, the highlighted significance of seed selection and placement as a theme in Table 2 is consistent with studies showing that dispersal without species and habitat matching results in inefficient ecosystem regeneration outcomes ([González-Castro et al., 2015](#), [Shaw et al., 2020](#)).

The prioritisation of restoring damaged lands and invasive species control (Figure 6) for seed dispersal reinforces the understanding that post-disturbance environments suffer from species recruitment issues ([Mendes et al., 2024](#)), and pressure from invasive species further undermines biodiversity regeneration ([Linders et al., 2019](#), [Dyderski & Jagodziński, 2020](#)). This expands on earlier literature by suggesting that autonomous technology for seed dispersal is more valuable when applied in high-disturbance contexts than in more stable, relatively disturbed environments. This contributes knowledge to the research gap identified earlier that focused on remote degraded ecosystems, where there was little research reviewing which ecological contexts can benefit the most from restoration technology.

The thematic analysis (Table 3) through affinity diagramming highlighted the reliability of autonomous seed dispersal as a severe limitation. Data revealed seed flow blockage issues due to the demonstrated drone device's inability to optimally adapt to various seed types. This supports earlier benchmarking information, which addressed that dispersal effectiveness depends not only on device functionality but also on seed material properties ([Sharma et al., 2024](#)). One valuable aspect of the findings was that it extended the earlier literature research that prioritised the ecological aspect of the research question, by detailing technical constraints that limits dispersal effectiveness.

The findings strongly demonstrated that autonomous-driven operations remain heavily human dependent, which was surprising. The volume of tasks requiring persistent and tedious manual labour, like dispersal calibration, seed refilling and battery replacement, raises questions about whether current systems can be considered truly autonomous. This consideration adds depth to the research gap by demonstrating that autonomy in ecological contexts is relative, potentially suggesting that persistent human involvement is necessary to ensure desired outcomes.

Design implications

Based on the findings, several key considerations can be suggested for the design of autonomous seed dispersal technology used for biodiversity restoration. Dispersal effectiveness is not defined by the device's ability to disperse and cover large areas with seeds, but by the suitability of seeds to site conditions and the ability to adapt to different seed types to ensure consistent reliability. It can be strongly suggested that designs prioritise the need to incorporate adaptable functions capable of handling a wide variety of seed types without being vulnerable to technical issues like blockage or damage. As drone dispersal is the most common method in the industry, targeting improvements to existing solutions could address the significant theme of reliability. This could involve improved internal mechanisms and perhaps introduce monitoring features that detect and report flow irregularities during operation.

Another highly promising design direction would be to develop dispersal methods that enhance germination success rather than focusing solely on seed distribution. This can also be approached by designing supportive functions such as watering systems or soil preparation to create optimal conditions that increase seed germination. This would move the design beyond dispersal to consider the early stages of plant growth.

Addressing the impact of invasive species would be highly recommended. The presence of invasive plants and their rapid colonisation of degraded dispersal sites was highlighted as a strong concern by findings. This suggests that design implications should not only focus on effective dispersal but also target strategies for monitoring, controlling, or displacing invasive species to create ideal conditions for plant repopulation, ensuring successful restoration outcomes.

Design implications should also prioritise reducing human reliance. Although the existing solutions examined in observation videos demonstrated autonomous seed dispersal functions, they required a substantial amount of repetitive and frustrating manual labour. The findings suggest opportunities for design improvements that reduce difficult labour, such as automated calibration systems, ergonomic-focused interactions for tasks like refilling and transport, or docking systems for convenient battery replacement. Alleviating physical demands would allow the design to better take advantage of autonomy while improving user engagement.

Conclusion

The research question, "How might autonomous technology be effectively implemented by environmental initiatives in supporting seed dispersal to remote wilderness land regions experiencing biodiversity degradation?" was investigated. Benchmarking and findings suggested that while autonomous solutions offer significant potential, their effectiveness is limited by many ecological and technical variables revealed by analysis and findings. Research surveys produced expert-driven data that focused on the scientific aspects relevant to the topic, while archival video observations focused on exploring the technical aspects of autonomous seed dispersal technology. The research was then used to inform design implications that could address the research question. However, the validity of findings could be strengthened with a larger survey sample, as only six experts participated in the research.

References

Academic & literature sources:

- Artamendi, M., Martin, P. A., Bartomeus, I., & Magrach, A. (2025). Loss of pollinator diversity consistently reduces reproductive success for wild and cultivated plants. *Nature Ecology Evolution*, 9(1), 296-313. <https://www.nature.com/articles/s41559-024-02595-2?fromPaywallRec=false#Abs1>
- Beckman, N. G., & Sullivan, L. L. (2023). The Causes and Consequences of Seed Dispersal. *Annual Review of Ecology, Evolution, and Systematics*, 54(1), 403-427. <https://doi.org/10.1146/annurev-ecolsys-102320-104739>
- Bomfim, J., Guimarães Jr, P. R., Peres, C. A., Carvalho, G., & Cazetta, E. (2018). Local extinctions of obligate frugivores and patch size reduction disrupt the structure of seed dispersal networks. *Ecography*, 41(11), 1899-1909. <https://nsojournals.onlinelibrary.wiley.com/doi/full/10.1111/ecog.03592>
- Castro, J., Morales-Rueda, F., Alcaraz-Segura, D., & Tabik S. (2022). Forest restoration is more than firing seeds from a drone. *Restoration Ecology*, 31(1), Article e13736. <https://onlinelibrary.wiley.com/doi/full/10.1111/rec.13736>
- Cazetta, E., & Fahrig, L. (2021). The effects of human-altered habitat spatial pattern on frugivory and seed dispersal: a global meta-analysis. *Okios*, 2022(2), Article e08288. <https://nsojournals.onlinelibrary.wiley.com/doi/full/10.1111/oik.08288>
- Doherty, K. D., Butterfield, B. J., Wood, T. E. (2017). Matching seed to site by climate similarity: Techniques to prioritize plant materials development and use in restoration. *Ecological Applications*, 27(3), 1010-1023. [https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.1505#:~:text=Current%20guidelines%20for%20the%20use,fungal%20symbiotes%20\(Joshi%20et%20al.](https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.1505#:~:text=Current%20guidelines%20for%20the%20use,fungal%20symbiotes%20(Joshi%20et%20al.)
- Dyderski, M. K., & Jagodziński, A. M. (2020). Impact of Invasive Tree Species on Natural Regeneration Species Composition, Diversity, and Density. *Forests* 2020, 11(4), Article 456. <https://www.mdpi.com/1999-4907/11/4/456>
- Fontúrbel, F. E., Candia, A. B., Malebrán, J., Salazar, D. A., González-Browne, C., & Medel, R. (2015). Meta-analysis of anthropogenic habitat disturbance effects on animal-mediated seed dispersal. *Global Change Biology*, 21(11), 3951-3960. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.13025?saml_referrer
- Fricke, E. C., Bello, C., Chaplin-Kramer, R., Dent, D. H., Feeley, K. J., Galetti, M., González-Varo, J. P., Heleno, R., & Reid, J. L. (2025). Drivers and impacts of global seed disperser decline. *Nature Reviews Biodiversity*, 1(1), 386-400. <https://www.nature.com/articles/s44358-025-00053-w#citeas>
- Godínez-Alvarez, H., Ríos-Casanova, L., & Peco, B. (2020). Are large frugivorous birds better seed dispersers than medium- and small-sized ones? Effect of body mass on seed dispersal effectiveness. *Ecology and Evolution*, 10(12), 6136-6143. <https://onlinelibrary.wiley.com/doi/full/10.1002/ece3.6285>
- González-Castro, A., Calviño-Cancela, M., & Nogales, M. (2015). Comparing seed dispersal effectiveness by frugivores at the community level. *Ecology*, 96(3), 808-818. <https://doi.org/10.1890/14-0655.1>
- Hernandez, J. O., Naeem, M., & Zaman, W. (2023). How Does Changing Environment Influence Plant Seed Movements as Populations of Dispersal Vectors Decline?. *Plants*, 12(7), Article 1462. <https://www.mdpi.com/2223-7747/12/7/1462>

- Jakovac, C. C., Junqueira, A. B., Crouzeilles, R., Peña-Claros, M., Mesquita, R. C.G., & Bongers, F. (2021). The role of land-use history in driving successional pathways and its implications for the restoration of tropical forests. *Biological Reviews*, 96(4), 1114-1134.
<https://onlinelibrary.wiley.com/doi/full/10.1111/brv.12694>
- 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. *Standards for Native Seeds in Ecological Restoration*, 28(3), 256-265.
<https://onlinelibrary.wiley.com/doi/full/10.1111/rec.13140>
- Lamichhane, J. R., Debaeke, P., Steinberg, C., You, M. P., Barbetti, M. J., & Aubertot, J. (2018). Abiotic and biotic factors affecting crop seed germination and seedling emergence: a conceptual framework. *Plant and Soil*, 432(1), 1-28.
<https://link.springer.com/article/10.1007/s11104-018-3780-9>
- Linders, T. E., Schaffner, U., Eschen, R., Abebe, A., Choge, S. K., Nigatu, L., Mbaabu, P. R., Shiferaw, H., & Allan, E. (2019). Direct and indirect effects of invasive species: Biodiversity loss is a major mechanism by which an invasive tree affects ecosystem functioning. *Journal of Ecology*, 107(6), 2660-2672.
<https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2745.13268>
- Lososová, Z., Axmanová, I., Chytrý, M., Midolo, G., Abdulhak, S., Karger, D. K., Renaud, J., Van Es, J., Vittoz, P., & Thuiller, W. (2023). Seed dispersal distance classes and dispersal modes for the European flora. *Global Ecology & Biogeography*, 32(9), 1485-1494.
<https://onlinelibrary.wiley.com/doi/full/10.1111/geb.13712>
- 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(2), 77-84.
<https://onlinelibrary.wiley.com/doi/10.1111/rec.12332>
- Mahant, V., & Pal, P. (2025). Seeding the future: a review of artificial intelligence's pivotal role in seed technology. *Journal of Crop Science and Biotechnology*, 28(1), 307-320.
<https://link.springer.com/article/10.1007/s12892-025-00284-5#Sec1>
- Mendes, S. B., Olesen, J. M., Memmott, J., Costa, J. M., Timóteo, S., Dengucho, A., & Craveiro, L. (2024). Evidence of a European seed dispersal crisis. *Science*, 386(6718), 206-211.
<https://www.science.org/doi/full/10.1126/science.ado1464>
- Neuschulz, E., Mueller, T., Schleuning, M., & Böhning-Gaese, K. (2016). Pollination and seed dispersal are the most threatened processes of plant regeneration. *Scientific Reports*, 6(1), Article 29839.
<https://www.nature.com/articles/srep29839#citeas>
- Ong, L., McConkey, K. R., & Campos-Arceiz, A. (2021). The ability to disperse large seeds, rather than body mass alone, defines the importance of animals in a hyper-diverse seed dispersal network. *Journal of Ecology*, 110(2), 313-326.
<https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2745.13809>
- Ribeiro da Silva, F., Montoya, D., Furtado, R., Memmott, J., Pizo, M. A., & Rodrigues, R. R. (2015). The restoration of tropical seed dispersal networks. *Restoration Ecology*, 23(6), 852-860.
<https://doi.org/10.1111/rec.12244>
- Robinson, J. M., Harrison, P. A., Mavoa, S., & Breed, M. F. (2022). Existing and emerging uses of drones in restoration ecology. *Methods in Ecology and Evolution*, 13(9), 1899-1911.
<https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/2041-210X.13912>
- Rossander, M., & Lideskog, H. (2023). Design and Implementation of a Control System for an Autonomous Reforestation Machine Using Finite State Machines. *Forests*, 14(7), Article 1340.
<https://www.mdpi.com/1999-4907/14/7/1340>

Sampaio, A. D., Pereira P. F., Nunes, A., Clemente, A., Salgueiro, V., Silva, C., Mira, A., Branquinho, C., & Salgueiro, P. A. (2021). Bottom-up cascading effects of quarry revegetation deplete bird-mediated seed dispersal services. *Journal of Environmental Management*, 298(1), Article 113472.

<https://www.sciencedirect.com/science/article/abs/pii/S0301479721015346>

Sharma, S., Dixit, A. K., & Saxena, S. (2024). Evaluating the Utilization of Unmanned Aerial Vehicles for Afforestation. *2024 International Conference on Electrical Electronics and Computing Technologies*, 1(1), 1-6.

<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10739181>

Shaw, N., Barak, R. S., Campbell, R. E., Kirmer, A., Pedrini, S., Dixon, K., & Frischie, S. (2020). Seed use in the field: delivering seeds for restoration success. *Standards for Native Seeds in Ecological Restoration*, 28(3), 276-285.

<https://onlinelibrary.wiley.com/doi/full/10.1111/rec.13210>

Sperry, J. H., O'Hearn, D., Drake, D. R., Hruska, A. M., Case, S. B., Vizentin-Bugoni, J., Arnett, C., Chambers, T., & Tarwater C. E. (2021). Fruit and seed traits of native and invasive plant species in Hawai'i: implications for seed dispersal by non-native birds. *Biological Invasions*, 23(1), 1819-1835.

<https://doi.org/10.1007/s10530-021-02473-z>

Stamatopoulos, I., Le, T. C., & Daver, F. (2024). UAV-assisted seeding and monitoring of reforestation sites: a review. *Australian Forestry*, 87(2), 90-98. <https://doi.org/10.1080/00049158.2024.2343516>

Teixido, A. L., Fuzessy, L. F., Souza, C. F., Gomes, I. N., Kaminski, L. A., Oliveira, P. C., & Maruyama, P. K. (2022). Anthropogenic impacts on plant-animal mutualisms: A global synthesis for pollination and seed dispersal. *Biological Conservation*, 266(1), Article 109461.

<https://www.sciencedirect.com/science/article/pii/S0006320722000143>

Tucker, M. A., Busana, M., Huijbregts, M., Ford, A. T. (2021). Human-induced reduction in mammalian movements impacts seed dispersal in the tropics. *Ecology*, 44(6), 897-906.

<https://nsojournals.onlinelibrary.wiley.com/doi/full/10.1111/ecog.05210>

Young, L. M., Kelly, D., & Nelson, X. J. (2012). Alpine flora may depend on declining frugivorous parrot for seed dispersal. *Biological Conservation*, 147(1), 133-142.

<https://www.sciencedirect.com/science/article/abs/pii/S0006320711004861>

UN.ESCAP. (2022). *SDG 15: Life on land: protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*.

<https://repository.unescap.org/items/9381ae06-7e12-4588-8229-0feadccc357f>

Vidal, M. M., Pires, M. M., & Guimarães Jr, P. R. (2013). Large vertebrates as the missing components of seed-dispersal networks. *Biological Conservation*, 163(1), 42-48.

<https://www.sciencedirect.com/science/article/pii/S000632071300092X#s0020>

Archival observation videos:

Video One:

Purdue Extension - Forestry and Natural Resources. (2022, February 22). *Drone Seeding for Native Grasses and Forbs* [Video]. YouTube.

https://www.youtube.com/watch?v=ceZp28QC4g&ab_channel=PurdueExtension-ForestryandNaturalResources

Video Two:

Agri Spray Drones. (2024, August 1). *Spreading Cover Crop Seed with Spray Drones* [Video]. YouTube.

https://www.youtube.com/watch?v=2g7JWYsho3I&ab_channel=AgriSprayDrones

Video Three:

Institute for Sustainability, Energy, and Environment at the University of Illinois. (2023, October 3). *DRONE COVER CROP SEEDING AT I-FARM* [Video]. YouTube.

https://www.youtube.com/watch?v=NNzTvX39zqU&ab_channel=InstituteforSustainability%2CEnergy%2CandEnvironmentattheUniversityofIllinois

Other online sources – Used for Benchmarking & Product Images:

AirSeed. (n.d.). *Our Technology*.

<https://www.airseedtech.com/our-technology>

Continental Engineering Services. (2024). *Advancing Reforestation with the Tree Seeding Robot*.

<https://conti-engineering.com/advancing-reforestation-with-the-tree-seeding-robot/>

DJI Agriculture. (2025). *DJI AGRAS 100*.

<https://aq.dji.com/t100>

FarmDroid. (n.d.). *FarmDroid Seeding System: Maximizing Yield with High Precision*.

<https://farmdroid.com/products/farmdroid-fd20/>

Hekkert, G. (2024). Continental and Land Life develop Tree Seeding Robot for reforestation.

<https://www.futurefarming.com/tech-in-focus/continental-and-land-life-develop-tree-seeding-robot-for-reforestation/>

LandLife. (n.d.). *Revolutionizing Reforestation: introducing Tree Seeding Robot*.

<https://landlifecompany.com/en-au/updates/revolutionizing-reforestation-introducing-tree-seeding-robot>

NuWay Ag. (2025, July 17). *First Flight with the T100: DJI's Spray Titan!* [Video]. YouTube.

https://www.youtube.com/watch?v=zBI1z1q8rqA&ab_channel=nuWayAg

Rees, C. (2022). *Seed Pod Delivery System Developed for Tree-Planting Aerial Drone*.

<https://www.citewrite.qut.edu.au/cite/#apa-internet-webpage>

Sheth, S. (2021). *Tiny autonomous solar-powered robot roams around on deserts, planting seeds to cultivate greenery*.

<https://www.yankodesign.com/2021/12/17/tiny-autonomous-solar-powered-robot-roams-around-on-deserts-planting-seeds-to-cultivate-greenery/>

END OF REPORT