Posted on 26 Aug 2025 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.22541/au.175622436.63027828/v1 — This is a preprint and has not been peer-reviewed. Data may be preliminary.

UAV-Based Precision Seed Dropping for Automated Reforestation

Qi Rui Lee[1], Henrik Hesse[1], Khuanphirom Naruangsri[2], Worayut Takaew[2], Stephen Elliot[2], and Dinesh Bhatia[3]

[1]University of Glasgow James Watt School of Engineering
[2]Chiang Mai University
[3]RMIT University

August 26, 2025

Abstract

Wildfires and deforestation pose significant threats to forest ecosystems, highlighting the need for large-scale initiatives to restore destroyed forest areas. Traditional reforestation methods are labor-intensive and require extensive infrastructure to cultivate a variety of native forest seedlings in nurseries. To enable large-scale direct seeding of native species, this paper presents the design, development, and field evaluation of a UAV-based seed-dropping system. The approach integrates a novel mechanical gravity-drop seeding mechanism with a multirotor UAV programmed to autonomously deploy individual seeds at target locations. The system uses biochar-coated seed balls, which facilitate the handling of multiple seed varieties and enhance overall germination success. Field evaluations at an active reforestation site in Northern Thailand have demonstrated the feasibility of the proposed solution in hilly remote areas representative of reforestation projects. Operating at a height of 4 m, the system achieves approximately 90% deployment success, with an accuracy within 1 meter of targeted locations. Unlike conventional aerial seeding systems, the proposed precision seed-dropping approach significantly reduces seed wastage, making the solution scalable to large-scale ecological restoration and biodiversity recovery initiatives.

UAV-Based Precision Seed Dropping for Automated Reforestation

---

Qi Rui Lee
James Watt School of Engineering
University of Glasgow
Glasgow, United Kingdom

Henrik Hesse*
James Watt School of Engineering
University of Glasgow
Glasgow, United Kingdom

Khuanphirom Naruangsri
Forest Restoration Research Unit
Chiang Mai University
Chiang Mai, Thailand

Worayut Takaew
Forest Restoration Research Unit
Chiang Mai University
Chiang Mai, Thailand

Stephen Elliot
Forest Restoration Research Unit
Chiang Mai University
Chiang Mai, Thailand

Dinesh Bhatia
School of Science, Engineering & Technology
RMIT University
Ho Chi Minh City, Vietnam

Abstract

Wildfires and deforestation pose significant threats to forest ecosystems, highlighting the need for large-scale initiatives to restore destroyed forest areas. Traditional reforestation methods are labor-intensive and require extensive infrastructure to cultivate a variety of native forest seedlings in nurseries. To enable large-scale direct seeding of native species, this paper presents the design, development, and field evaluation of a UAV-based seed-dropping system. The approach integrates a novel mechanical gravity-drop seeding mechanism with a multirotor UAV programmed to autonomously deploy individual seeds at target locations. The system uses biochar-coated seed balls, which facilitate the handling of multiple seed varieties and enhance overall germination success. Field evaluations at an active reforestation site in Northern Thailand have demonstrated the feasibility of the proposed solution in hilly remote areas representative of reforestation projects. Operating at a height of 4 m, the system achieves approximately 90% deployment success, with an accuracy within 1 meter of targeted locations. Unlike conventional aerial seeding systems, the proposed precision seed-dropping approach significantly reduces seed wastage, making the solution scalable to large-scale ecological restoration and biodiversity recovery initiatives.

Keywords: UAV, Reforestation, Seed-Based Restoration, Automated Seeding, Precision Agriculture

1 Introduction

After logging, wildfires have become one of the leading drivers of forest loss, destroying millions of hectares of vegetation each year. Recent examples include catastrophic fires in North America that have devastated forests in California, Oregon, and British Columbia, leaving behind degraded landscapes with limited potential for natural regeneration (British Columbia, 2025). In Australia, fires of 2019-2020 burned over 24 million hectares and displaced nearly three billion animals (Noble, 2020). Similar trends persist in Brazil's Amazon basin and across parts of tropical Asia. In particular, the evergreen forests of Northern Thailand remain highly vulnerable to large-scale wildfires during the dry season (Ong et al., 2025; Puttapirat et al., 2024). These seasonal fires not only disrupt forest ecosystems and accelerate biodiversity loss but also significantly degrade air quality, leading to increased respiratory illnesses that affect millions of people every year (Chen & Kocha, 2023).

---

*Corresponding author: `henrik.hesse@glasgow.ac.uk`

In response to the challenges, the United Nations Decade on Ecosystem Restoration Program (United Nations, 2021) and the Trillion Trees Initiative (WWF, 2025) have emerged as global efforts to reverse ecosystem degradation through large-scale reforestation. These programs emphasize the urgent need to restore forest ecosystems not only to sequester atmospheric carbon dioxide but also to rebuild biodiversity, stabilize water and soil quality, and support local livelihoods. Other regional efforts further align with these global initiatives, such as Canada's 2 Billion Trees program and the Woodland Trust rainforest project in the southwest of England (Cruz, 2025). In Southeast Asia, the Forest Restoration Research Unit at Chiang Mai University (FORRU-CMU) has implemented rigorous reforestation programs across Northern Thailand for over two decades to support the recovery of forest ecosystems in the areas affected by wildfires (Elliott et al., 2013).

However, conventional reforestation methods rely on nursery propagation and manual planting of seedlings at the remote restoration sites. While ecologically effective, this approach is inherently slow, labor-intensive, and logistically demanding. Scaling such operations to hundreds of thousands of hectares, as proposed under the UN or WWF initiatives, becomes almost impossible. To overcome these limitations, there is increasing interest in the use of Unmanned Aerial Vehicles (UAVs) to automate and accelerate reforestation efforts. Recent developments in UAV-based seed dispersal offer a promising alternative by enabling rapid deployment of seeds across remote areas. Several commercial initiatives have demonstrated the feasibility of this approach. For example, companies like Flash Forest in Canada, AirSeed Technologies in Australia, and Dendra Systems in Europe have developed UAV technologies to support the reforestation of areas affected by environmental damage (Asher, 2023; Nonko, 2023; Walker, 2021). These examples highlight the potential of UAV technologies to support large-scale restoration efforts through rapid deployment, reduced cost, and improved access to otherwise inaccessible terrain. However, despite these recent developments, UAV-based reforestation remains underutilized in many regions, including Southeast Asia and especially in biodiversity hotspots like Northern Thailand. There is a clear need for systematic research and validation of UAV-based seeding as an established tool for ecological restoration. This is particularly important in the context of global reforestation targets, such as those set by the United Nations Decade on Ecosystem Restoration (Castro et al., 2024). This paper therefore explores the design and development of a UAV system for precision seed dropping in the context of reforestation applications in Northern Thailand. The work aims to address key challenges in automated reforestation systems, including seed delivery accuracy, operational reliability, and deployment efficiency, with the goal to contribute a scalable and adaptable approach for future reforestation programs.

1.1 Problem Statement: Reforestation Efforts in Northern Thailand

The Forest Restoration Research Unit at Chiang Mai University (FORRU-CMU) has developed reforestation strategies across Northern Thailand for over two decades. The work aims to accelerate the natural regeneration of biodiversity-rich upland evergreen forests using scientifically informed methods, including the Framework Species Method (FSM) (Elliott et al., 2013). This approach promotes natural forest regeneration by planting carefully selected native tree species characteristic of the target forest to rapidly establish canopy cover, suppress weeds, and attract seed-dispersing wildlife (Elliott et al., 2013; Elliott et al., 2020; Lu et al., 2017). FORRU-CMU has conducted extensive nursery and field research to identify suitable framework tree species for restoration, validated across more than 42 sites covering over 50 hectares.

While conventional reforestation methods have proven effective in restoring degraded sites, their application to landscape-level projects remains limited due to extensive infrastructure and accessibility requirements. The process typically involves seedling development through large-scale nursery programs and subsequent manual planting at the reforestation site, which requires road access to restoration sites, production of containerized seedlings, and transportation of heavy planting stock to often remote and inaccessible areas (Goldapple, 2017). High labor demands, operational costs, and terrain limitations ranging from muddy ground to steep hills pose additional safety and logistical challenges for planting seedlings (Stamatopoulos et al., 2024). To address these challenges, direct seeding presents a promising alternative to conventional tree planting whereby seeds are sown directly into the soil at the restoration sites. By eliminating the need for nursery infrastructure, direct seeding is typically cheaper, requires less labor, and simplifies logistics, as seeds are easier to transport to remote locations compared to containerized seedlings. In Thailand, the feasibility of direct seeding for forest restoration has been evaluated in the northern seasonally dry forests, where seeds are typically sown at the beginning of the rainy season when conditions are optimal for germination and root development (Naruangsri et al., 2023; Waiboonya & Elliott, 2020). Despite these advantages, direct seeding is often associated with lower establishment rates when compared to nursery-grown seedlings (Grossnickle & Ivetić, 2017). It therefore requires careful planning to be effective in reforestation, including species selection, quality seed sourcing, effective site preparation, and post-sowing monitoring (Elliott et al., 2020). Previous work has identified native forest tree species suitable for direct seeding in Northern Thailand's biodiversity-rich upland evergreen forests (Naruangsri et al., 2024).

However, direct seeding faces significant challenges limiting widespread adoption for large-scale restoration, with removal by wildlife being a major obstacle (Naruangsri et al., 2023; Woods & Elliott, 2004). Especially in exposed landscapes that lack natural cover, seeds become easy targets for consumption and displacement by animals. Another issue is the result of blanket seeding, which spreads seeds randomly over the terrain, leading to uneven seed distribution and undesirable tree clusters (Stamatopoulos et al., 2024; Tamura et al., 2017). The combination of these factors results in significant seed wastage. Hence, to achieve desired restoration outcomes, direct seeding requires a much larger amount of seeds compared to nursery-based seedlings. This makes direct seeding unsustainable for large-scale projects, which naturally demands a reliable and continuous seed supply (Velasquez-Camacho et al., 2021). To overcome these challenges, seed coating has emerged as a promising solution (Allen, 2007; Fukuoka, 2013). Inspired by agricultural permaculture practices, encapsulating seeds in biodegradable coating material creates a secure environment for germination and reduces predation risks (Taylor et al., 2020; K. Zhang et al., 2022). Depending on the approach, coatings can be thin films, nutrient-rich encrusting, or fully-enclosed spherical pellets (Javed et al., 2022). Among these, seed pelleting offers advantages for forest restoration by improving mechanical handling and reducing seed loss to predation (Afzal et al., 2020; Berto et al., 2024). Encasing irregularly shaped seeds produces uniform, spherical seed balls as shown in Figure 1. This process facilitates the automated dispersal of differently sized seeds and also helps to improve the overall sowing efficiency (Naruangsri, 2023). Hence, the reduced seed wastage using seed balls enables direct seeding as a viable strategy for large-scale reforestation projects where seed availability is often a limiting factor.


(a) Example seed ball morphology.
(b) Example of seed ball deployed at site.

Figure 1: Overview of biochar-based seed balls used in this study to incorporate *Sarcosperma arboreum* seeds.

In this work we aim to explore the use of seed balls to facilitate UAV-based aerial seeding in automated reforestation initiatives. Previous research by FORRU-CMU evaluated the coating of multiple native tree species, comparing biochar, soil mixture, and polysaccharide mixtures to study the effect of seed coating on seed predation. Biochar-based seed balls demonstrated the highest effectiveness in reducing seed removal compared to non-coated seeds (Naruangsri, 2023; Naruangsri et al., 2024). Based on these studies, *Sarcosperma arboreum* seeds were selected for this work. The seeds typically exhibit an oblong shape measuring 22±1 mm by 11±1 mm and a mass of 1.3±0.2 grams. To produce the seed balls, the Nendo Dango technique was applied using biochar from longan wood mixed with clay soil at a 1:1 ratio (Fukuoka, 2013; Naruangsri, 2023). The resulting spherical seed balls shown in Figure 1 are uniform, with a diameter of 30 mm and an average mass of 17.5 grams each. These specifications directly inform the constraints for the design of the UAV-based seed dispensing mechanism. The seed ball parameters outlined here will be considered as design requirements considered in Section 2.2.

1.2 Related Work: UAV-Based Aerial Seeding

Integrating the use of UAVs in reforestation strategies provides huge opportunities to advance ecological restoration and forest management. As demonstrated by the commercial examples above, UAV-based aerial seeding enables efficient direct seeding for large-scale reforestation projects (Elliott et al., 2020). Several studies have proposed the use of UAVs in automated reforestation, leveraging the capabilities of UAVs across multiple stages of the reforestation life cycle (Castro et al., 2024; Mohan et al., 2021; Stamatopoulos et al., 2024). Following established practices in agriculture (Kim et al., 2019), a typical UAV-supported restoration workflow considers:

- Aerial surveys using multispectral and LiDAR sensors to assess site conditions, vegetation cover, and identify optimal habitats for seed placement (Mohan et al., 2021). Spatial analysis to inform species selection, such as FSM to identify native tree species best suited for the targeted forest ecosystem (Elliott et al., 2013).
- Seed dispersal using UAVs equipped with specialized seeding mechanisms and programmed to follow an optimized flight path to seed targeted areas (Kaushikkar & Whitman, 2023)
- Post-deployment monitoring using UAV surveys to evaluate seedling establishment, vegetation growth, and overall ecosystem recovery to inform adaptive management practices, including resowing additional seeds or weeding of affected areas (Mohan et al., 2021). Long-term ecological impact assessments, such as mapping carbon sequestration, to evaluate the contribution of reforestation efforts toward climate change mitigation (Dainelli et al., 2021).

The effectiveness of UAV-based reforestation is driven by the performance of the seed dispersal mechanisms. Most UAV seed-dispersal technologies originate from agricultural applications typically handling small seeds such as rapeseed, rice, or wheat (Huang et al., 2020; Kim et al., 2019). However, native tree seeds in tropical forests normally vary greatly in size. For example, our study in Naruangsri et al. (2024) considered 23 native species with seeds ranging from 0.02-4.26 g. However, for direct seeding, we focus on medium-sized seeds (0.1–2 g dry mass) and large seeds (greater than 2 g dry mass), which tend to be more successful in degraded areas (Naruangsri et al., 2024; Tunjai, 2011). Given these requirements, UAV-compatible seed dispersal systems must be lightweight and robust, versatile enough to accommodate diverse seed morphologies, and capable of precisely controlling the timing and spatial distribution of seed release. These factors drive the design process of UAV seed-dispersal systems, which can be broadly classified by their distribution mechanisms as described next (Mohan et al., 2021).

Gravity-Drop Seeding Systems are widely employed in large-scale agricultural operations for distributing seeds, fertilizers, or animal feed from hoppers. These systems can be categorized into either constant mass flow or precision drop devices (Lysych et al., 2021). Constant mass flow devices use stationary openings controlled by flaps or shutter mechanisms similar to camera apertures, which can be adjusted to regulate the sowing rate (Karademir, 2025). More advanced constant mass flow mechanisms employ fluted rollers or rotating drums driven at constant speeds to achieve more consistent seed release rates (Kus, 2021). But these methods are not suitable for targeted seeding operations in reforestation projects. Instead, *precision drop systems* aim to enhance seed placement accuracy through mechanical mechanisms such as rotating discs or vacuum-based approaches (Zhong et al., 2024). Vacuum-based systems use suction to securely hold and precisely release seeds from perforated discs. This offers high precision and uniform spacing common in ground-based agricultural machinery. However, adapting vacuum suction systems to UAVs is challenging due to the weight and complexity of the required vacuum systems. Regardless of the underlying mechanical design, gravity-based systems are vulnerable to environmental factors, including wind conditions, UAV propeller downwash, and altitude, which can significantly affect seed dispersion accuracy (Zhu et al., 2025).

Other common seeding mechanisms used in agriculture consider *Centrifugal Seeding Systems* which incorporate fast-spinning discs to radially accelerate and evenly distribute seeds over targeted areas (Song et al., 2018). Similar to constant mass flow devices, centrifugal seeding systems cannot control the release of individual seeds for precision applications, leading to seed wastage and making this approach less suitable for UAV-based reforestation applications. Centrifugal systems are often integrated with *Airflow Seeding Systems* where airflow generated by fans directs seeds through nozzles (Huang et al., 2020; Yuan et al., 2024). The speed and direction of the airflow can be adjusted to control the distribution pattern and density of the seed dispersal (Zhu et al., 2025). Despite the improved performance, airflow systems increase the mechanical complexity and weight of the seeding system, and they also lack the required precision. Finally, *Pneumatic Seeding Systems* use compressed air to propel seeds into the soil (X. Zhang et al., 2023). The system provides optimal placement precision and soil penetration, which can help germination and protect seeds from predation (Liu et al., 2023; Lysych et al., 2021). While the dispersal precision makes this seeding system ideal for reforestation projects, the complexity and weight of the pneumatic mechanisms lead to high payload requirements and much larger UAV systems. These systems also tend to block. To overcome this, seeds are typically encapsulated in standardized seed balls which also accommodate varying seed sizes and protect seeds during the impact.

1.3 Objectives and Scope

Despite the significant progress, existing UAV-based seeding systems are not viable for large-scale reforestation projects, especially in Northern Thailand where inaccessible terrain hinders the use of conventional UAV platforms. In this paper, we present the design, implementation, and field evaluation of an autonomous UAV-based seed-dropping system to support the reforestation activities at FORRU-CMU project sites. Considering the limitations of the presented state-of-the-art systems, the contributions of this paper are summarized as follows:

- We propose the design of a mechanical seed dropping mechanism, which is sufficiently compact for UAV-based seeding solutions and enables precision seed dispersal for large-scale reforestation studies.
- We present the integration of the seeding mechanism with a multirotor UAV platform for automated seeding missions. We consider flight control and sensor fusion to enable the autonomous UAV operation in hilly terrain.
- We evaluate the performance and reliability of the UAV-based seeding system in extensive lab and field tests, and discuss pathways to scale the concept to large-scale reforestation missions.

The remainder of the paper is organized as follows. Section 2 details the concept, hardware design, and software implementation of the UAV-based seed dropping platform. Section 3 presents the experimental evaluation of the system, including indoor validation results and initial field tests. Section 4 discusses the field implementation in Northern Thailand. Section 5 discusses the insights gained from field tests and concludes the paper with suggestions for large-scale implementation.

2 Concept, Design, and Implementation of Seed Dropping System

2.1 System Overview

The UAV-based seed dropping system presented in this paper integrates a custom-designed dispensing mechanism onto a quadrotor UAV platform to enable precision aerial seeding for reforestation applications. As shown in Figure 2, the system is composed of two major subsystems: (1) the quadcopter UAV platform, and (2) the proposed seed delivery mechanism.

(a) Conceptual design with seed mechanism in gray.

(b) Field testing of the actual system.

Figure 2: System overview of the proposed UAV-based seed-dropping mechanism.

The HolyBro X500 V2 quadcopter UAV used in this work provides a versatile aerial platform commonly considered for aerial robotics research projects (Holybro, 2025). The platform supports open-hardware and open-source development, making it easily configurable and well-suited for experimental studies. The UAV is powered by four KV920 brushless motors. According to the manufacturer's specifications, the baseline system can deliver a maximum combined thrust of approximately 5 kg using 10-inch propellers. Considering an empty mass of 1.15 kg including the battery, the platform can carry a payload of up to 1.35 kg while maintaining adequate thrust-to-weight margins of 50% for safe and stable flight (Ong et al., 2019). Together with the specifications of the seed balls in Section 1.1, the technical specification of the HolyBro system in Table 1 defines the initial design constraints of the baseline UAV system. A detailed analysis of the system, including a detailed thrust analysis, will be discussed in Section 3. The UAV is further equipped with a Pixhawk 6C flight controller capable of operating ArduPilot or PX4 firmware (Pixhawk, 2024). We will use the ArduPilot environment in this work to implement the fully autonomous seeding operation through pre-programmed waypoint missions and event-triggered payload control, as introduced in Section 2.4. The flight endurance was assessed through experimental flight tests using a 5,000 mAh LiPo battery under no-payload conditions, resulting in an average flight time of approximately 18 minutes. Through the preliminary flight tests, we evaluated the system stability under various loads to ensure adequate flight performance and endurance. This provides the starting point to define the design requirements for this proof-of-concept study.

Table 1: Technical specifications of Holybro X500 V2 UAV (Holybro, 2025).

Parameter	**Value**
Wheelbase	500 mm
Empty Mass	610 g
Battery Mass (5,000 mAh LiPo)	542 g
Allowable Payload Mass	1,350 g
Flight Time (under no-payload)	18 minutes

The selected carriage-based seed dropper was integrated with the UAV frame using a lightweight bracket to mount the proposed seed dispersal mechanism. The system feeds seed balls through a translating carriage actuated by a servo motor. This allows individual seed balls to be dispensed one at a time with controlled positioning as required for the reforestation problem statement considered in this work. A micro limit switch installed at the outlet provides feedback to the operator or flight control software that individual seeds have been dropped successfully. Section 2.2 summarizes the details of the design process for the seed dropping mechanism considering the design requirements and constraints of the UAV system.

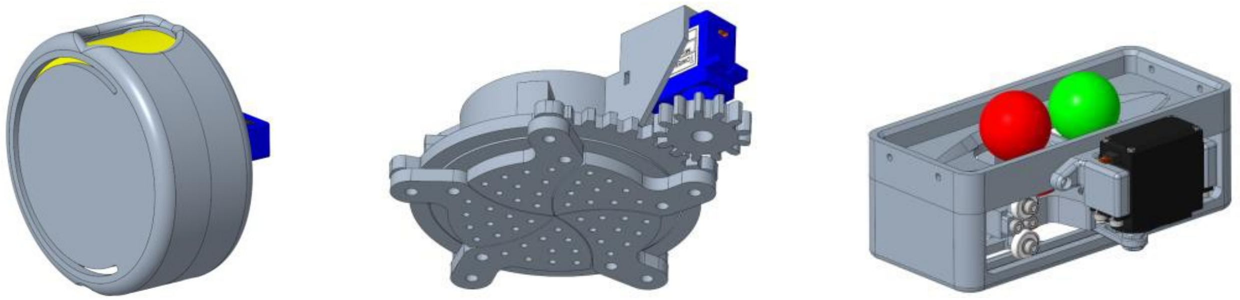
2.2 Design of Seed Dropping Mechanism

The success of the reforestation system greatly depends on the precision and reliability of the seeding operation, which defines specific design requirements for the seed dropping mechanism as summarized in Table 2. As presented in Section 1.2, most UAV-based seeding operations use blanket seeding methods (Stamatopoulos et al., 2024), where seeds are dispersed broadly along the flight path. This results in low establishment rates as seeds may accumulate unevenly. To improve reforestation outcomes, we aim to design a seed dispersal mechanism with controlled seed placement to reduce seed wastage and to increase ecological effectiveness. As precision seeding systems using pneumatic mechanisms can be prone to jamming, we emphasize not only precision but also reliability in the design requirements. Additionally, we have considered the UAV specifications in Table 1 which pose additional design constraints limiting the size, payload capacity, and flight endurance.

Table 2: System design specifications of UAV-based seed dropping mechanism.

Aspect	**Objective**	**Criteria**
UAV Function	Autonomous route following	UAV with autonomous waypoint following.
Reliability	Consistent seed dropping	Seed dropping mechanism to achieve at least 90% success rate in seed deployment per mission.
Capacity	Maximize seed capacity	Tank to hold a minimum of 30 seed balls.
Performance	Seed dispensing speed	Dispense at least 1 seed ball per second.
Precision	Seed metering rate	Controlled seed dispensing, one seed ball per command.
Mass	Adhere to payload limits of the UAV	Total mass of mechanism should not exceed allowable payload mass of 1,000 g.

We applied the total design methodology by Pugh (1991) to generate design concepts and compare them consistently against design requirements in Table 2. Based on a market survey of available commercial products and the designs reviewed in Section 1.2, we generated three initial seed dropper concepts which meet the product design specifications in Tables 1-2. Figure 3 presents the considered design concepts which were evaluated using 3D modeling and simulation to assess mechanical feasibility and compatibility with the UAV platform. We limited the design scope to gravity-drop, mechanical mechanisms for precision dispersal, as pneumatic systems were deemed too heavy and unreliable given the design requirements (Lysych et al., 2021). Similar to the design by Zhong et al. (2024), the *Rotating Drum Concept* is a cylindrical seed selector which consists of a drum with a single hole. A servo motor is integrated to rotate the drum, allowing individual seed balls to be released through the outlet. The *Aperture Concept* feeds seed balls into an iris mechanism (Karademir, 2025). A servo motor rotates the actuator ring, which opens the iris blades allowing seed balls to pass through the aperture. Finally, the proposed *Carriage Mechanism Concept* is a novel concept which has not been explored previously for precision seeding operations. The mechanism consists of a translating carriage which moves laterally upon servo actuation. When a seed ball inside the slot aligns with the seed outlet, the seed ball is dropped through the outlet.



(a) Concept 1: Rotating Drum

(b) Concept 2: Aperture

(c) Concept 3: Carriage Mechanism

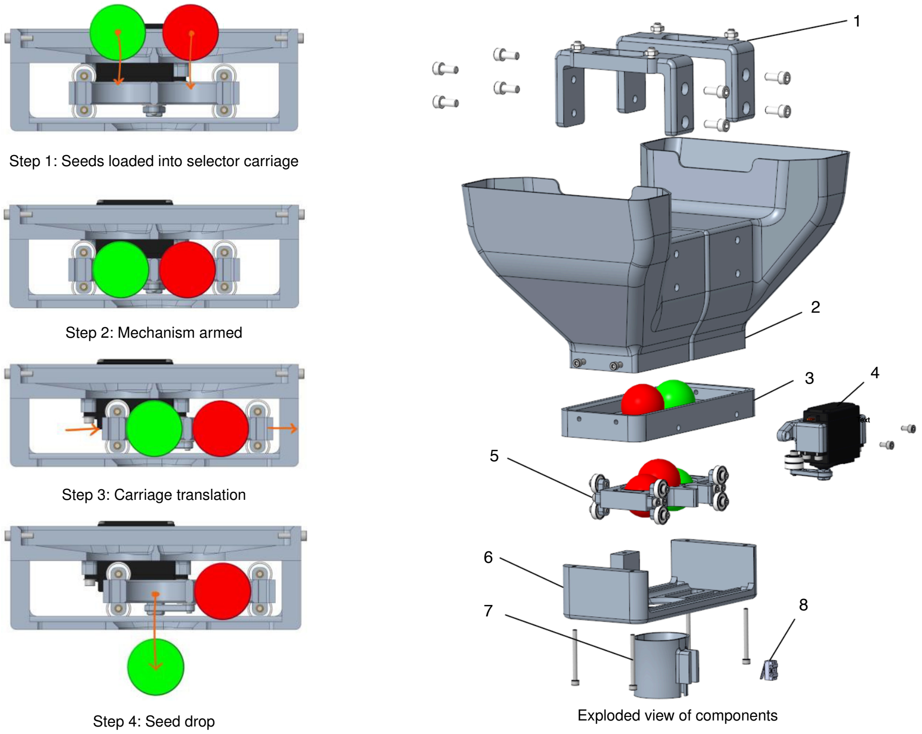
Figure 3: Generated conceptual designs for the seed-dropping mechanism.

Following the total design methodology (Pugh, 1991), a Pugh matrix was generated as a structured tool to compare the generated concepts against the design criteria defined in Table 2. Weightings were assigned based on their relevance to the UAV-based seed deployment requirements. Concept 3 (Carriage Mechanism) achieved the highest score, outperforming the other concepts in seed dispensing accuracy and versatility. It is also the only design that is capable of handling two distinct seed types in a single mechanism and offers precise, one-at-a-time release, which is critical for the UAV-based restoration of native forests.

2.2.1 Detailed Design of Carriage Mechanism for Precision Seed Dropping

Using Concept 3 as a starting point, a detailed design of the Carriage Mechanism was developed considering the structural and operational constraints of the UAV platform. The design boundaries included payload mass and mounting dimensions. We also ensured that the center of gravity remains at the center of the UAV to maintain stability (Ong et al., 2019). Figure 4 (right) shows the final design of the seed dropping mechanism fully integrated with the UAV frame. The seed hopper (item 2) is securely mounted onto the UAV with the mounting bracket (item 1). Each hopper (item 2) can carry 20 seed balls, which are fed into the seed selector carriage (items 3-6). The carriage is actuated by a servo motor (item 4) which translates the carriage horizontally to align a seed cavity with the outlet and to release a single seed per command. The outlet (item 7) integrates a limit switch sensor (item 8), which is used to detect the presence of seeds falling through the outlet. The limit switch provides real-time confirmation of each successful drop, enabling feedback to the ground station or operator (see software implementation in Section 2.4). The seed dropping mechanism follows a four-step actuation cycle as illustrated in Figure 4 (left).

This design enables discrete and repeatable seed deployment with high precision. The mechanism supports up to 40 seed balls per mission via two independent hoppers with a reduced risk of jamming and enabling simultaneous release of different tree species. The geometry was iteratively developed using simulation and fused deposition modeling 3D printing to reduce the overall weight while maintaining structural integrity. The 3D design considers the limitations of the additive manufacturing process, e.g. limiting the slope of the hopper walls. The total mass of the final design as shown in Figure 4 (right) is 660 g and considering that each of the 40 seed balls weighs 17.5 g, we are within the allowable payload capabilities of the UAV of 1,350 g. The effect of the additional payload on system performance and flight time will be evaluated in more detail in Section 3.3.



Step 1: Seeds loaded into selector carriage

Step 2: Mechanism armed

Step 3: Carriage translation

Step 4: Seed drop

Exploded view of components

Figure 4: Detailed design of a the seed-dropping mechanism with operational sequence (left) and with the exploded view of the components: (right): 1– Seed hopper mounting bracket, 2– Seed hoppers, 3– Seed guide, 4– Servo motor with arm and mount, 5– Seed selector carriage, 6– Seed outlet and carriage guide, 7– Outlet sensing attachment, 8– Micro limit switch.

2.3 UAV Integration

The final design of the seed dropper has been integrated with the HolyBro X500 V2 quadrotor platform, as shown in Figure 5. As introduced above, the HolyBro X500 V2 quadrotor features a modular carbon-fiber frame and an open-source architecture that facilitates the seamless integration of custom payloads. At the core of the system architecture is the Pixhawk 6C flight controller which, in this project, is running the ArduPilot firmware (details of the flight control software are presented in Section 2.4).

(a) Isometric view

(b) Bottom view

Figure 5: Final prototype with full integration of seed-dropping mechanism on HolyBro X500 V2 platform.

The Pixhawk flight controller allows the UAV to interface with various components to enable coordinated flight and payload control. Figure 6 details the system architecture with the interfaces between the different UAV components. The flight stack is integrated with standard components to support basic UAV operation: u-blox GPS module with integrated compass for global positioning and heading, a telemetry radio for real-time bidirectional communication with the Ground Control Station (GCS), and a Radio Control (RC) receiver for manual control of the UAV and override during safety-critical operations. The electrical power is managed by a central power module and distributed via a power distribution board, which regulates the nominal voltage of 14.8 V from the 4S 5000-mAh LiPo battery to the motors and the flight control board. An additional Battery Eliminator Circuit is used to step down the voltage to supply regulated power to the peripheral components, including the seed-dispensing servo motor and the limit switch at the outlet. Signal routing is handled through two separate Pulse Width Modulation (PWM) breakout boards, allowing parallel connection of the four motors and the actuators. The complete system architecture, wiring layout, and specification of the UAV components can be seen in Figure 6.

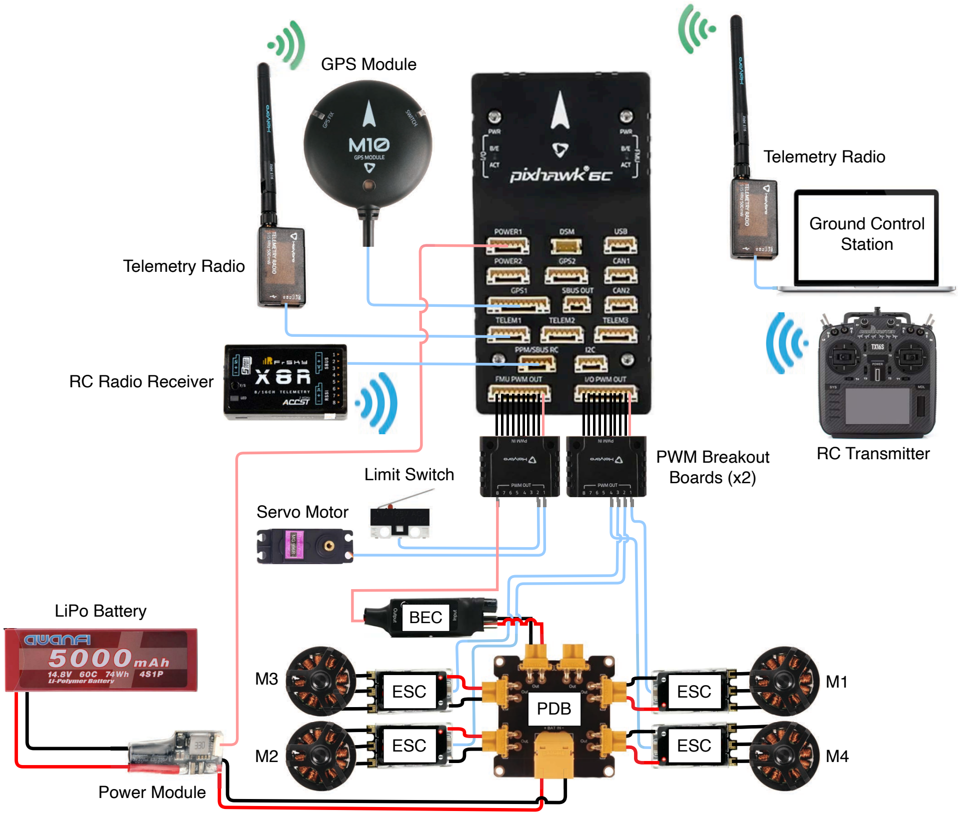


Figure 6: Overview of UAV component integration.

2.4 Software Architecture

The UAV system is managed using the ArduPilot firmware, which runs onboard the Pixhawk 6C flight controller (Pixhawk, 2024). ArduPilot is an open-source, comprehensive autopilot software environment to develop fully autonomous vehicles, providing advanced flight control capabilities, custom mission scripting, and flexible integration of sensors, actuators, and external logic. We use the Mission Planner software in conjunction with ArduPilot to implement the GCS interface (MissionPlanner, 2024). The Mission Planner environment provides UAV operators with tools for UAV setup, mission configuration, real-time telemetry monitoring, and data logging. These functions are implemented in this work to enable waypoint planning, low-level actuator control, and in-flight feedback monitoring required for autonomous seed deployment.

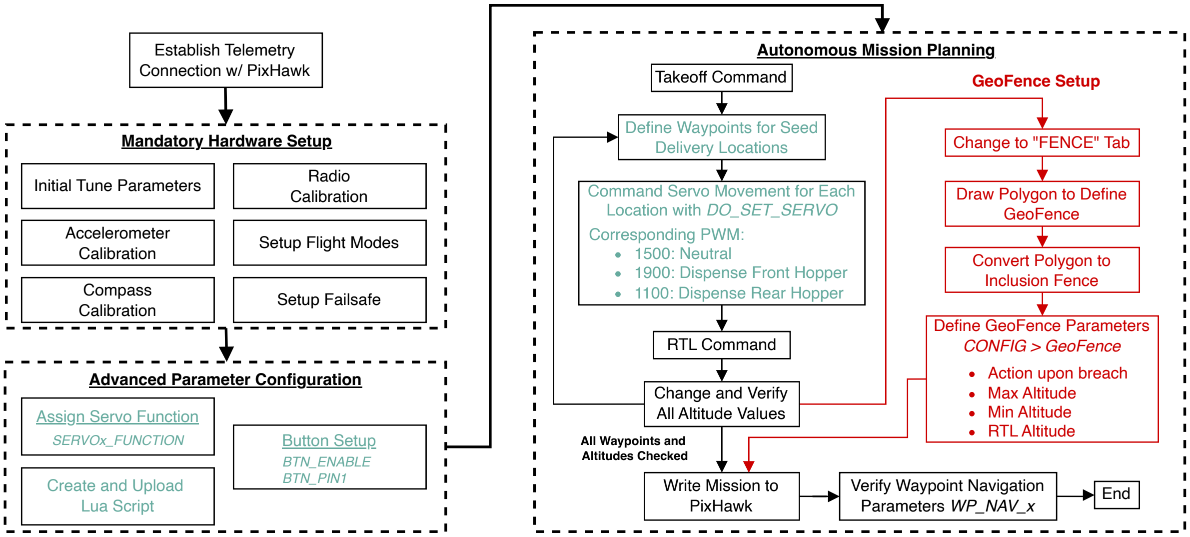


Figure 7: Flowchart of software implementation using Mission Planner ground control environment.

2.4.1 Basic UAV System Configuration

Figure 7 presents a summary of the required steps to configure the UAV system for automated seed dispensing. The initial configuration of the UAV system follows the mandatory setup through Mission Planner. The gains of the PID-based flight controller are initialized based on system specifications including propeller size, motor performance, and airframe size. The gains are subsequently adjusted following preliminary flight tests to account for the additional payload mass (Cheng et al., 2019). To enable autonomous flight mission profiles, we configured different flight modes using the RC transmitter to toggle between `Auto` and `Manual` modes. The UAV considers different failsafe scenarios in case the RC connection is lost or the batteries are low, triggering the automatic `RETURN_TO_LAUNCH` action to ensure that the UAV will return safely to the take-off position. As an additional safety feature, we implemented geofencing to restrict flight boundaries. Finally, to enable consistent seeding altitude over complex terrain, a downward-facing LiDAR (LightWare LW20C) was integrated into the flight control system for real-time terrain following during autonomous missions. This feature is useful for operations in mountainous regions, such as our test site in Northern Thailand, where reliance on global terrain maps (e.g. SRTM data) is insufficient due to low resolution and errors in local elevation maps. In `Auto` mode, the LightWare LW20C provides direct altitude-above-ground measurements of up to 100 m to dynamically adjust flight altitude along the mission path, ensuring uniform seeding height even along hillsides.

2.4.2 Implementation of Automated Seed Dropping

As detailed in Section 2.2, the seed-dispensing carriage is actuated by a servo motor. To command the servo, it is connected to the FMU PWM OUT port of the Pixhawk flight controller via a PWM breakout board (see Figure 6). The servo is configured in Mission Planner to respond to discrete PWM signals corresponding to three predefined carriage positions. A PWM signal of 1,500 holds the carriage in its neutral center position beneath the seed hopper, allowing it to load seeds (Steps 1–2 in Figure 4). PWM commands of 1,100 and 1,900 translate the carriage left or right, respectively, to release individual seeds from the rear or front hoppers (Steps 3–4). This enables the integration of the seed dispensing operation within the autonomous mission profile of the UAV.

A limit switch is mounted at the outlet of the seed-dispensing mechanism to provide confirmation of successful seed release at the pre-programmed drop locations. The switch is connected to the second PWM breakout board operating at 5 V and is configured as a digital General-Purpose Input/Output (GPIO) pin. This setup enables the Pixhawk flight controller to read the switch state directly as a digital input. To support in-flight monitoring, the switch was further configured in Mission Planner as a virtual button, allowing its state to be accessed via onboard Lua scripting. This configuration enables the system to register each seed drop event and transmit confirmation messages to the GCS in real time. The total number of drops is stored as an onboard variable and displayed on the GCS during flight. Full details of the Lua script implementation are presented in Appendix A.

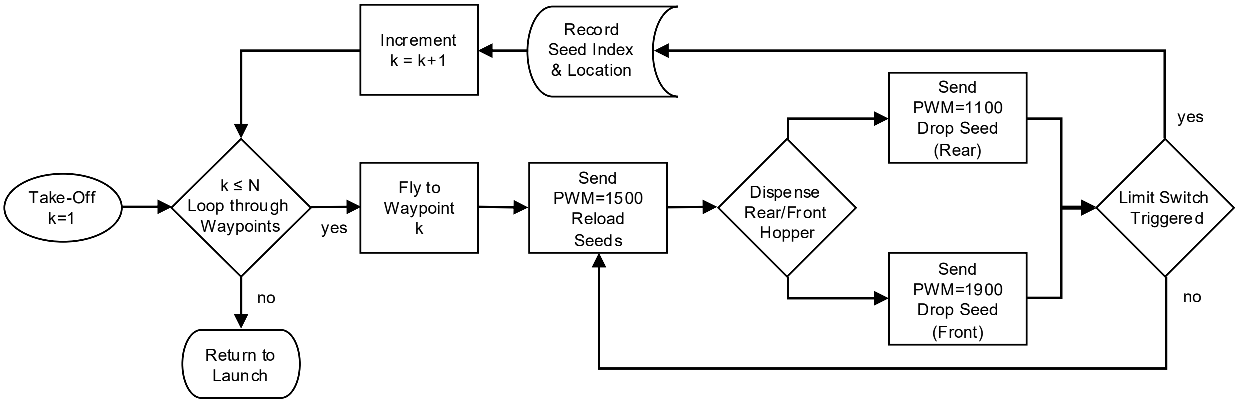


Figure 8: Flowchart of mission profile for automated seed dispensing at N locations.

Mission profiles for the automated seeding operation are developed through Mission Planner by sequentially assigning MAVLink-compatible commands such as `TAKEOFF`, `WAYPOINT`, and `RETURN_TO_LAUNCH`. The seed release is commanded via `DO_SET_SERVO` to deliver PWM signals to the servo motor controlling the seed-dispensing carriage. As shown in Figure 8, the mission iterates through each waypoint k commanding the servo to dispense a seed from the appropriate hopper using a defined sequence of PWM signals: 1,500 to return the carriage to its neutral loading position to reload seeds, followed by 1,100 or 1,900 to dispense a seed from the rear or front hopper, respectively. The sequence can be adapted to missions where different seed types are loaded in the front and rear hoppers, enabling selective release of seeds. The limit switch confirms each successful drop, which is logged and transmitted to the GCS. The mission concludes with an automatic return-to-launch sequence when all N waypoints have been completed. The implementation of the seed dropping mechanism, mission profile, and UAV flight control has been evaluated in detail in Section 3.

3 Field Evaluation

Preliminary flight experiments were conducted to evaluate the performance of the proposed UAV-based seed dispersal concept. The aim was to assess the UAV flight performance, system implementation, and seed dropping accuracy. As indicated in Figure 9, these initial test flights were conducted at two locations. The netted futsal court (Location 1) provided a controlled environment for initial safety checks and hover tests, while the outdoor field test (Location 2) allowed us to assess the full mission implementation under real-world outdoor conditions. Both environments were geofenced, as shown in Figure 9.

3.1 UAV Flight Characteristics

Two configurations of the UAV were evaluated in the initial flight testing, one with an empty seed tank and another with eight seed-balls (four in each hopper). The corresponding mass breakdowns are presented in Table 3. Testing both configurations allowed us to compare the battery consumption, thrust-to-weight ratios, and hover performance with the manufacturer's specifications in Table 1. We used the flight log data extracted from the onboard Pixhawk flight controller to discuss the UAV flight characteristics.

3.1.1 Flight Endurance and Thrust Performance

To determine the flight endurance, we conducted hover endurance tests by flying the UAV manually in *Loiter* and *PosHold* modes using the loaded and unloaded configurations. In both configurations, the UAV demonstrated stable flight lasting 13 min 46 s for the unloaded configuration and 11 min 51 s for the loaded configuration. Here, we considered that LiPo batteries should not be discharged below 20% capacity to maintain safe battery health (Ong et al., 2019). While flight times may vary slightly in real-world scenarios due to wind and maneuvering, the flight times are sufficient for short seeding missions in this proof-of-concept implementation. For more realistic missions, the seed dropping concept can be translated to larger UAVs for extended flight times.

Figure 9: Flight testing locations with their respective planned autonomous mission waypoints (green markers) and geofences (blue markers): 1- Netted Futsal Court; 2- Outdoor field.

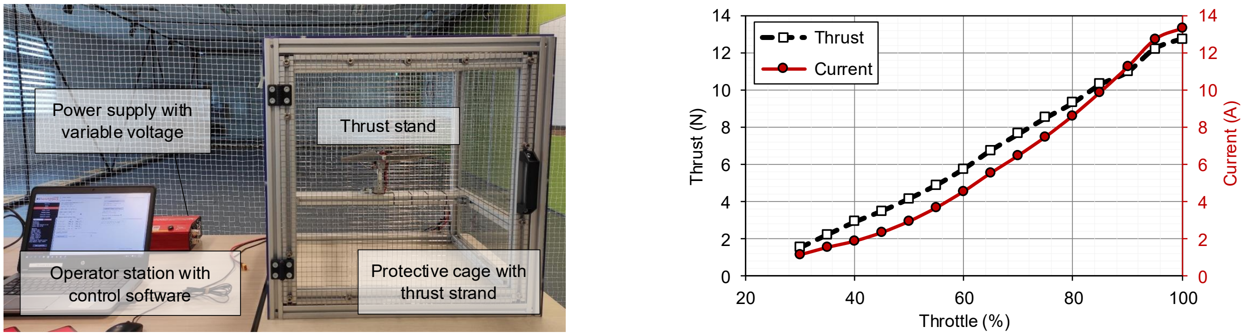
Table 3: Mass statement of completed prototype and flight test configurations.

		Empty Configuration	**Seed Drop Configuration**
Empty Mass	HolyBro X500 V2	1,121 g	1,121 g
Fixed Payload	Seed-dropping Mechanism LiPo Battery (5,200 mAh)	660 g 542 g	660 g 542 g
Variable Payload	Seed-balls	0 g	17.5 × 8 = 140 g
	Total Mass	**2,324 g**	**2,464 g**

To ensure that the UAV can safely operate in a fully loaded configuration, we further considered the thrust-to-weight (T/W) ratio of the UAV system, calculated as

$$T/W\ Ratio = \frac{Max\ Combined\ Thrust}{UAV\ Takeoff\ Weight} \quad (1)$$

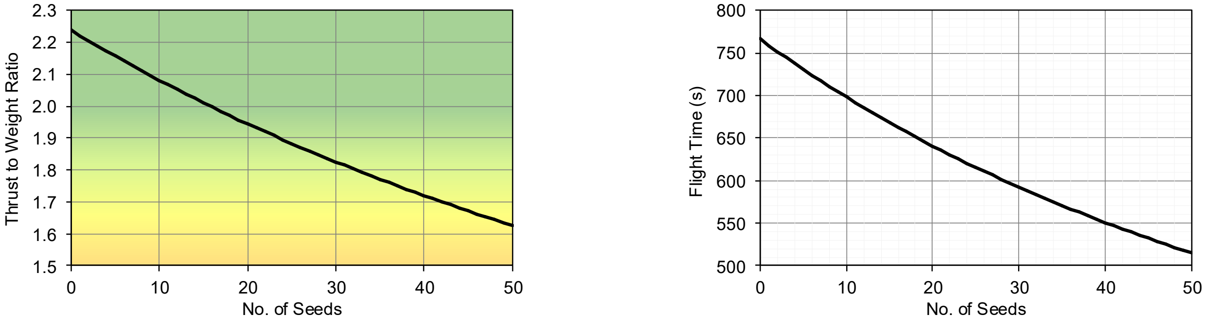
We used the RCbenchmark Series 1585 Test Stand as shown in Figure 10 to measure the produced thrust and power requirements at different throttle settings (Chew et al., 2021). Each rotor provides up to 12.8 N of thrust, yielding a maximum combined thrust of 51 N for the quadcopter. With a takeoff weight of 22.8 N (empty) and 24.2 N (loaded with 8 seed balls), the corresponding T/W ratios are 2.24 and 2.11. T/W ratios above 1.9 typically provide sufficient performance to maintain stable flight even under mild wind conditions (Biczyski et al., 2020). Using the experimental thrust test results above, we conducted a broader performance assessment presented in Figure 11. The analysis shows how the *T/W Ratio* degrades with increasing number of loaded seed balls. The colored shading indicates acceptable *T/W Ratio* for sufficient flight performance (Putra et al., 2020). While it is still possible to fly outdoors at full hopper capacity (40 seeds), the low *T/W Ratio* = 1.73 means that the flight performance would be very sluggish and potentially infeasible in high-wind conditions. Hence, a loading of max. 30 seeds is suggested for the final field implementation in Northern Thailand to maintain sufficient maneuverability in realistic outdoor conditions. The expected flight time in Figure 11(b) was estimated using the required current draw (see Figure 10) assuming that 4,160 mAh battery capacity is available to maintain battery health. For a realistic mission with 30 seeds, the expected flight time would drop to approx. 10 min assuming constant loading of the seed numbers throughout the flight duration. However, in reality a slightly longer flight time can be expected as the payload weight reduces throughout the seeding mission.



(a) Setup of RCbenchmark Series 1585 Test Stand.

(b) Thrust stand results.

Figure 10: Experimental results of thrust performance for the 2216 KV920 motor with a 10-inch propeller.



(a) Thrust-to-weight ratio *T/W Ratio*.

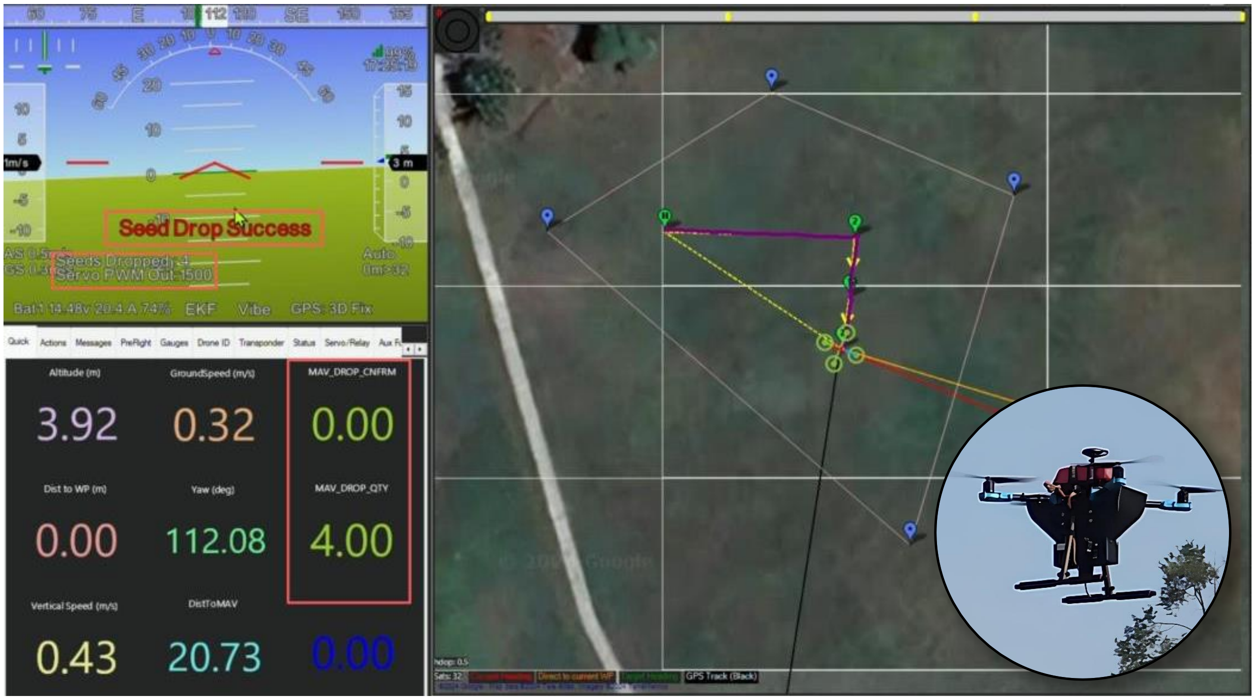
(b) Flight time.

Figure 11: Estimation of UAV thrust-to-weight ratio and flight time for a range of seed balls. Colored shading in (a) indicates feasible flight envelopes: *T/W Ratio* $<$ 1.6 indoor flight, 1.6 $\leq$ *T/W Ratio* $\leq$ 1.9 outdoor flight in light wind conditions, and *T/W Ratio* $>$ 1.9 outdoor flight in heavy wind conditions.

3.1.2 Autonomous Mission Performance

To evaluate the performance of the autonomous waypoint tracking and seed-dropping tasks, a representative mission using 4 seed balls was implemented and tested in an outdoor environment (see Location 2 in Figure 9). The mission includes a sequence of waypoints, representing typical restoration targets, and commands for seed-dispensing as described in Section 2.4.2. Figure 12 shows the mission dashboard during the autonomous operation. The UAV was commanded to ascend to an altitude of 4 m relative to the ground, navigate through a series of waypoints while maintaining a constant altitude above ground, dispense seeds at the defined locations, and return to the launch site. During the test flight, the UAV closely followed the planned trajectory (shown in yellow). However, minor altitude deviations were observed due to uneven terrain within the flight area. To mitigate this, a downward-facing LiDAR sensor was subsequently integrated into the system, as described in Section 2.4, enabling real-time terrain-following capabilities.

We also validated the Lua script which has been implemented to track the seed release, reading the limit switch sensor output, as described in Section 2.4.2. Figure 12 shows the real-time dashboard alerts that are displayed to the operator each time a seed is successfully dispensed, and a user-defined parameter (`MAV_DROP_QTY`) is incremented to show the total number of seeds released. This feedback mechanism improves mission oversight for the operator, and it enables cross-validation with ground-truth observation data during the post-deployment assessment phase. The implemented seed counter stores the geolocation of the actual seed drops. In future, this record can be used for ecological assessment and auditing of large-scale UAV-based reforestation missions.



Seed Drop Success

Seeds Dropped: 4
Servo PWM Out 1500

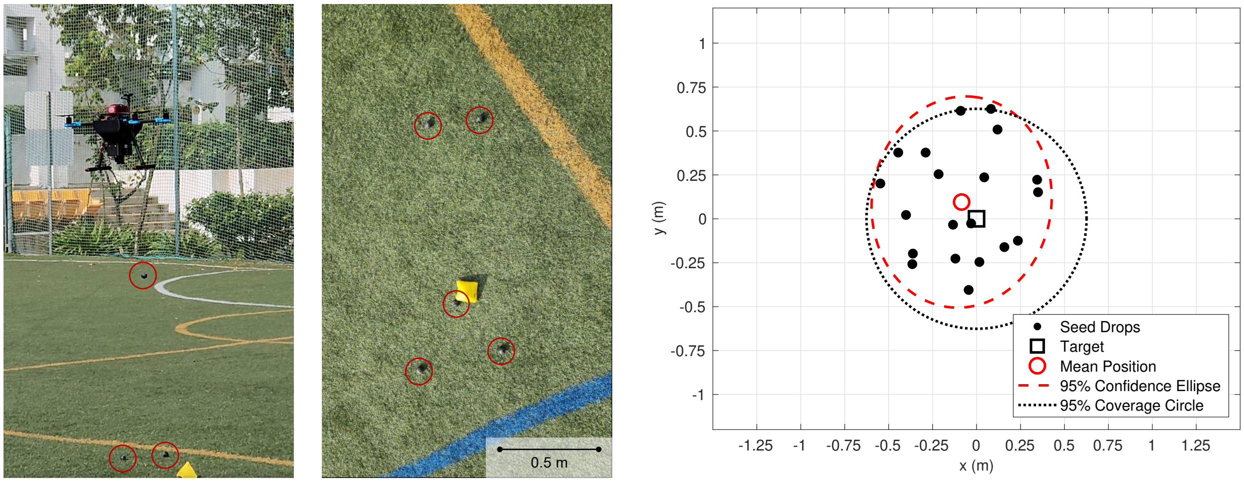
Bat1 14.48v 20.4 A 74% EKF Vibe GPS: 3D Fix

Altitude (m)	GroundSpeed (m/s)	MAV_DROP_CNFRM
3.92	0.32	0.00
Dist to WP (m)	Yaw (deg)	MAV_DROP_QTY
0.00	112.08	4.00
Vertical Speed (m/s)	DistToMAV	
0.43	20.73	0.00

Figure 12: Autonomous mission trajectory and initial field test of the UAV seed-dropping system. Waypoints are marked in green, geofence is outlined with blue markers, and UAV trajectory is shown in purple. Lua script provides feedback of seed drops to operator via the dashboard (highlighted with orange boxes).

3.2 Drop Accuracy and Placement Metrics

The accuracy of the seed dropping mechanism was assessed through flight tests conducted at the two locations indicated in Figure 9. Tests at the futsal court (Location 1) were limited to a maximum altitude of 1.5 m due to the height constraints imposed by the futsal netting. For the outdoor tests, multiple altitudes were evaluated, with 4 m found to provide the optimal balance. This altitude ensured clearance above weeds and bushes while reducing potential damage to seed balls from higher drop heights. Through these tests, we aimed to determine how seed dispersion patterns are influenced by drop height, surface topography, and environmental conditions.



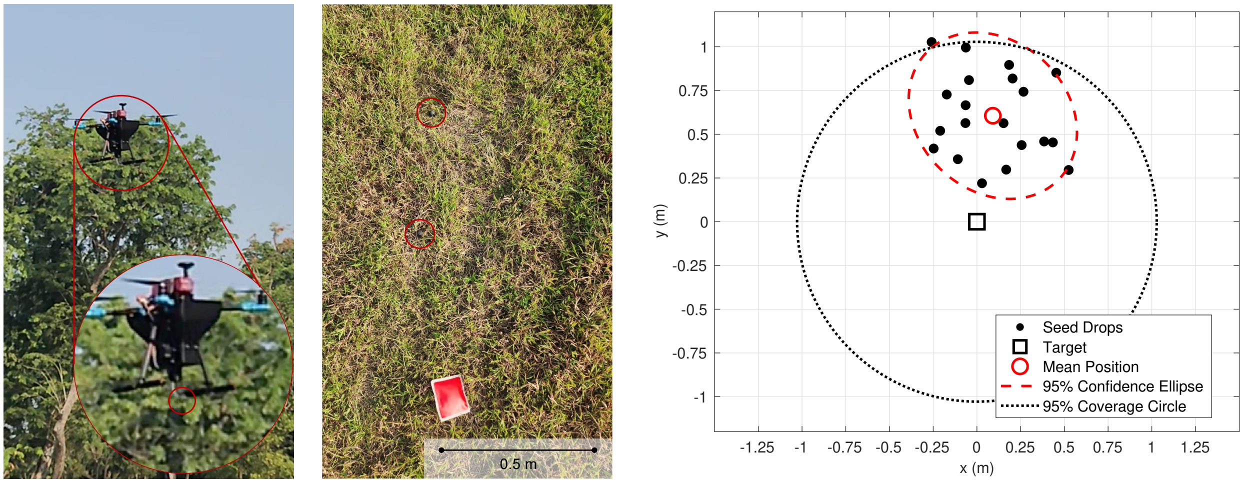
(a) UAV dispersing seeds.

(b) Seed dispersion pattern.

(c) Extracted coordinates of seeds after 20 drops.

Figure 13: Seed dispersion patterns observed during flight tests at futsal court (Location 1) from a drop altitude of 1.5 m.

Figure 13 illustrates the futsal court test results showing the seed drop pattern around the intended target locations under calm conditions (wind blocked inside the futsal court). The dispersion patterns were analyzed for 20 seeds using the mean offset, a 95% confidence ellipse (assuming a bivariate normal distribution), and a 95% coverage circle (based on radial distances from the target) for the evaluation. The mean position was within 0.13 m of the target position. However, the smooth surface caused the seed balls to bounce and roll after the initial impact, which resulted in a larger radial standard deviation of 0.29 m. Nonetheless, the 95% coverage circle shows reliable results, with most seeds landing within a radius of 0.63 m of the intended target.



(a) UAV dispersing seeds.

(b) Seed dispersion pattern.

(c) Extracted coordinates of seeds after 20 drops.

Figure 14: Seed dispersion patterns observed during flight tests at Location 2 from a drop altitude of 4 m.

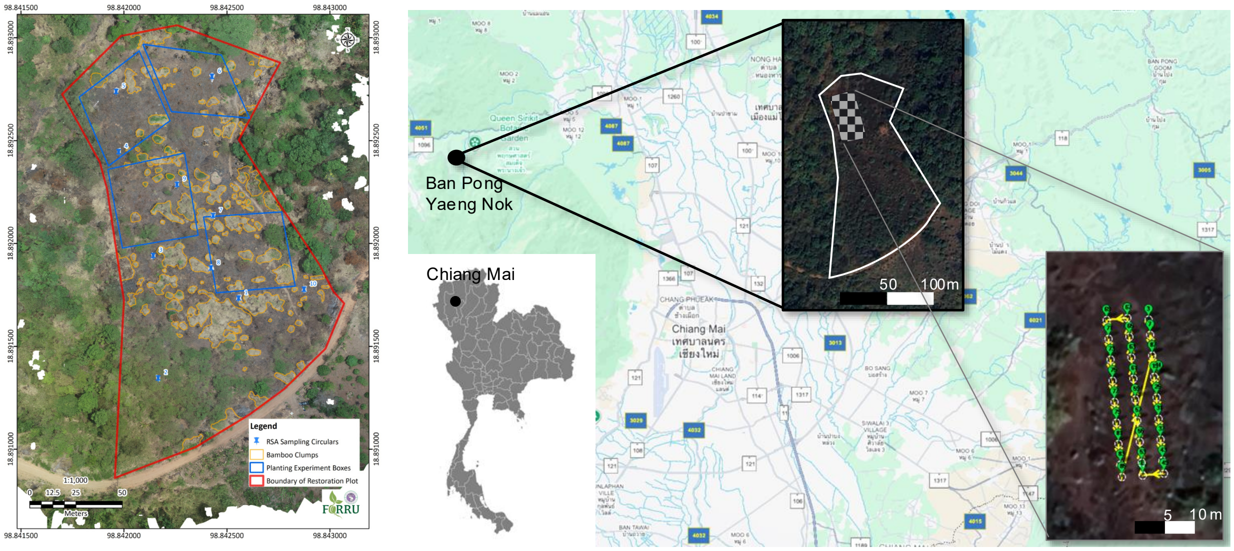
Figure 14 presents the results from the outdoor test (Location 2), conducted under light wind conditions at 4 m altitude. During the autonomous mission defined in Figure 12, four seed drops were commanded with two from the rear hopper at the first waypoint and two from the front hopper at the second waypoint. The experiment was repeated five times to get 20 representative seed drops. As illustrated in Figure 14, a lateral bias in drop accuracy was observed, resulting in a mean offset of 0.61 m from the intended target location. This larger offset is likely due to the effect of wind or a slight misalignment of the GNSS locations. However, the grassy surface helped the seed balls to land smoothly with minimal rolling observed. This leads to a reduced radial standard deviation of 0.24 m and a 95% confidence ellipse, as plotted in Figure 14. Overall, most seeds landed within 1.03 m of the intended target, as illustrated by the 95% coverage circle.

3.3 Discussion of Preliminary Field Evaluation

The field experiments presented in this section provide a preliminary validation of the UAV-based seed dispersal concept under realistic conditions. A total of 40 seed drops were analyzed across two test sites. The controlled environment of the futsal court (Location 1) allowed us to safely evaluate the system reliability and dispersion geometry under calm conditions, while the open field tests (Location 2) introduced realistic disturbances in terms of wind conditions, terrain topography, and navigation accuracy. The smoother ground condition at the futsal court caused a larger variance in the seed dispersion as compared to grassy conditions at Location 2. This finding is particularly relevant when considering deployment over smooth (dry soil) or rougher (grass or weed) surfaces. In addition, we observed a minor offset from the target locations for the outdoor tests, which was likely due to light wind conditions and potential GNSS inaccuracies. Nonetheless, all seed drops remained within 1 m of the intended target location, as captured by the 95% coverage circle. These results show that the developed seed-dropping system can be used successfully for the reforestation mission at the FORRU-CMU test site. However, the results also highlight the importance of considering the surface characteristics and environmental conditions when planning the aerial seeding operations using gravity-drop systems.

4 Field Implementation for Automated Seeding in Northern Thailand

To evaluate the feasibility of autonomous aerial seeding, a structured field trial was conducted at a FORRU-CMU reforestation site near Ban Pong Yaeng Nok in Chiang Mai Province, Thailand, as shown in Figure 15. The bamboo-deciduous plot covers approximately 16,000 m^2 at an altitude ranging from 790 to 800 m. A fire during the 2024 dry season (January to April) severely damaged the site, resulting in significant tree mortality. In response, approximately 3,500 trees were planted in July 2024 before the rainy season as part of FORRU-CMU's ongoing restoration efforts (Laohasom, 2024). Figure 15a shows details of the original reforestation efforts.



(a) Original reforestation plan by FORRU.

(b) Flight path for aerial seeding, green markers indicate defined flight mission.

Figure 15: Location of field site for reforestation near Ban Pong Yaeng Nok in Thailand.

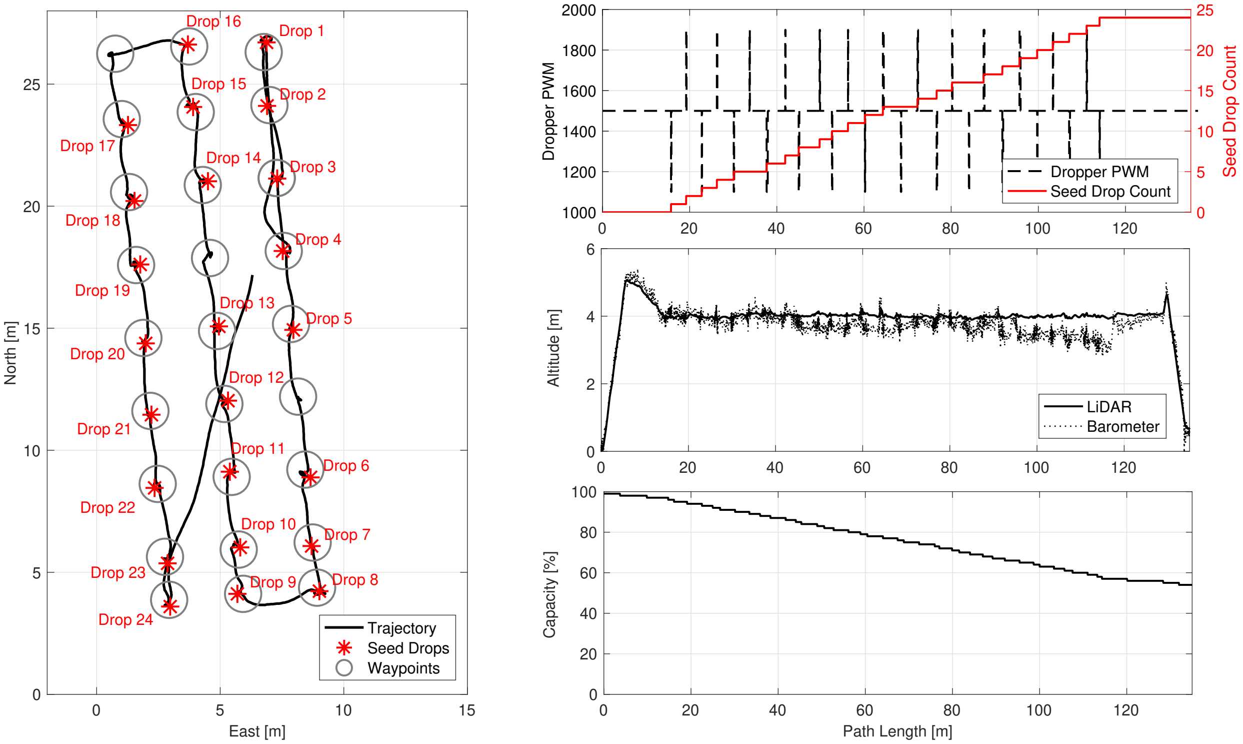
A 600 m^2 rectangular area within this site was considered to implement the automated UAV-based seeding system (see checkered area in Figure 15b). We used Mission Planner to generate a regular grid of waypoints spaced 3 m apart, resulting in 27 waypoints to cover the designated test area. We ensured that for this mission we remained below 30 seeds to ensure satisfactory UAV flight performance, as analyzed in Section 3.1.1. The spacing matches the spacing and position of the young trees already planted at the plot. The UAV flight mission is illustrated in Figure 15b with the green markers indicating the planned waypoints. As described in Section 2.4.2, the UAV was programmed to follow the trajectory autonomously and release a seed at each waypoint. Terrain following was achieved by maintaining a relative altitude of 4 m using the onboard LiDAR sensor for altitude control. A geofence was defined to constrain the autonomous flight within the site boundaries of the checkered area for operational safety.

As FORRU-CMU had already planted trees at the allocated test site in July 2024, we used the current tree location for comparison to evaluate the seed dropping accuracy. Figure 16 illustrates the field condition during the dry season in February 2025, when the field trials were conducted. Seeding operations are not normally done during dry seasons, as the lack of rain prevents seed germination. However, during this period, the terrain is relatively clear from weeds, which makes it possible for us to do a visual inspection of the seed drops, as shown in Figure 16(a). Figure 16(b) shows examples of the seed drops comparing the actual seed location (red) with the target position (blue) where the trees have been planted. All seeds landed within 0.5 m of the intended locations, demonstrating the successful deployment of the seed dropping mechanism.

Figure 17 presents the detailed analysis of the seeding mission with Figure 17(a) showing the actual UAV trajectory overlaid with the waypoints (gray circles) defined in Mission Planner. The mission lasted 390 seconds and the UAV covered a total flight path of 135 m. The red markers show the position of successful seed drops. Of the 27 seeds planned for the deployment, 24 were confirmed as successful drops. The implemented onboard script (see Section 2.4.2) records the GNSS location of each successful deployment. The position information will be used in future work by FORRU-CMU to monitor germination rates and for ecological assessment.

(a) View of field site after completed UAV mission. (b) Example seed locations (red) with respect to target locations (blue).

Figure 16: Confirmation of seed locations after the automated seeding mission at the Ban Pong Yaeng Nok field site.



(a) UAV trajectory with targets and actual seed drops. (b) Details of UAV parameters during the UAV mission.

Figure 17: Details of the automated seed dropping mission at the Ban Pong Yaeng Nok site.

Figure 17(b) plots the UAV parameters against the cumulative path length of the mission. The top plot shows the PWM signals sent to the seed dropping servo alternating between 1,100 and 1,900 (black curve) to indicate the commanded seed release from the front and rear hoppers, respectively. The red curve shows the sequence of recorded seed releases, which has been obtained from the logged limit switch actuations, indicating successful seed drops. It is clear that the hopper failed to release 3 seeds, which is due to seeds sporadically jamming the hopper. But the mechanism is able to release the jam for the next seed release. The experimental tests show that the proposed mechanism can achieve almost 90% success rate. The center subplot in Figure 17(b) compares the UAV altitude derived from the downward-facing LiDAR versus the barometric sensor. Although the test site is relatively flat, minor variations are apparent. The LiDAR-based terrain-following system was able to maintain an accurate 4 m target altitude, which demonstrates the effective tracking of the varying terrain topography. In contrast, barometric altitude measurements naturally show significant deviations as the barometric sensor cannot sense the actual terrain unevenness. The results highlight the need for a LiDAR-based system when considering the operation of UAV-based seeding systems in hilly terrain. Finally, the bottom subplot in Figure 17(b) tracks the battery capacity (as a percentage of the battery voltage). The mission consumed 46% of the total battery capacity over the 6.5-minute mission. Given that only 80% of nominal battery capacity is usable (to preserve battery health), this result aligns closely with the predicted endurance for 30-seed missions presented in Figure 11.

This initial field implementation as part of FORRU-CMU reforestation efforts proves the feasibility of the proposed seed dropping system in realistic reforestation scenarios, such as the restoration site in Ban Pong Yaeng Nok. The successful demonstration not only highlights the system's potential for effective reforestation efforts but also paves the way for larger-scale deployment in future.

5 Conclusion and Future Work

Traditional reforestation methods typically rely on growing seedlings in nurseries, which is often slow, labor-intensive, and difficult to implement at a large scale in remote areas. To address these constraints, this paper has presented the development of an automated UAV-based seed-dropping system equipped with a novel carriage-based seed dispensing mechanism designed to release individual seeds. Unlike heavier pneumatic seeding systems commonly used for precision aerial seeding, the proposed gravity-drop system is mechanically driven, allowing it to be easily integrated with various multirotor UAV platforms. The seeds have been coated with a biochar mixture to produce consistently spherical seed balls. The coating protects the forest seeds from predation and enables the handling of multiple seed varieties to use a mix of native species, which is critical to enhancing biodiversity and sustainable reforestation efforts. The seed dispersal mechanism has been implemented with an open-source UAV navigation system to enable automated seeding missions. The integrated downward-facing LiDAR improves the robustness of the flight control system, even in complex and hilly terrain, where UAV-based seeding can be a critical enabler for reforestation missions. To evaluate the success of the aerial seeding, a limit switch was integrated to provide real-time feedback on successful seed releases. The on-board script tracks the geolocation of all successful seed drops, which will allow us to track the development of seedlings as part of future large-scale reforestation campaigns.

The initial laboratory and flight tests confirmed the effectiveness of the proposed seeding mechanism and UAV integration. The field evaluations highlighted the impact of UAV altitude, terrain, and wind conditions on the seed deployment accuracy, with optimal results obtained at a flight altitude of 4 m. At this altitude, seeds consistently landed within 1 m of their intended targets under mild wind conditions and grassy terrain, which reduces the bouncing and rolling of seed balls. The final field evaluation demonstrated the successful deployment at an active reforestation site managed by the Forest Restoration Research Unit at Chiang Mai University in Northern Thailand. The field tests verified the system efficacy achieving 90% successful seed deployments at 27 planned target locations covering an area of 600 m^2. These field results highlight the system's potential for scalable, low-cost, and precise reforestation in inaccessible or degraded areas. By introducing the concept of multi-species hoppers, the system can help to enhance ecological diversity, support rapid restoration of degraded sites, and improve overall biodiversity efforts.

Although the current configuration is limited to 30 seed balls and a flight time of 10 minutes, the modular design allows the integration of the system with larger UAVs and seed hoppers. Expanding the deployment to larger UAV systems capable of extensive coverage and operational endurance will be crucial for scaling the demonstrated concept to landscape-level reforestation programs in the future. Finally, as this study primarily focused on the technological development of the aerial seeding system, further long-term ecological studies will be necessary to comprehensively evaluate the overall success of UAV-based reforestation using seed balls, including seedling establishment rates, survival, and broader ecological impact.

Acknowledgments

This work was supported by a grant from the APNIC Foundation, via the ISIF Asia Fund (Grant No: 202403-02759): FIREfly 2.0: Enhancing Forest Fire Monitoring and Biodiversity Conservation with a UAV Based IoT System. The authors received further support from the Forestry Restoration Research Unit at Chiang Mai University. The authors would also like to thank Steven Chua from the Singapore Institute of Technology for the technical support in the UAV development.

References

Afzal, I., Javed, T., Amirkhani, M., & Taylor, A. G. (2020). Modern Seed Technology: Seed Coating Delivery Systems for Enhancing Seed and Crop Performance. *Agriculture*, *10*(11), 526. https://doi.org/10.3390/agriculture10110526

Allen, J. (2007). *Smart Permaculture Design*. Australia, New Holland Publishers.

Asher, C. (2023). Cutting-edge drones give reforestation a helping hand. https://news.mongabay.com/2023/07/new-tree-tech-cutting-edge-drones-give-reforestation-a-helping-hand

Berto, B., Ritchie, A. L., & Erickson, T. E. (2024). Seed enhancements to improve direct-seeding outcomes for native grasses in mine restoration. *Frontiers in Ecology and Evolution*, *12*. https://doi.org/10.3389/fevo.2024.1405649

Biczyski, M., Sehab, R., Whidborne, J. F., Krebs, G., & Luk, P. (2020). Multirotor Sizing Methodology with Flight Time Estimation. *Journal of Advanced Transportation*, *2020*, 1–14. https://doi.org/10.1155/2020/9689604

British Columbia. (2025). British Columbia Wildfire Season Summary. https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-history/wildfire-season-summary#previous-wildfire-season-summaries

Castro, J., Alcaraz-Segura, D., Baltzer, J. L., Amorós, L., Morales-Rueda, F., & Tabik, S. (2024). Automated precise seeding with drones and artificial intelligence: a workflow. *Restoration Ecology*, *32*(5). https://doi.org/10.1111/rec.14164

Chen, H., & Kocha, O. (2023). Smoke from forest fires blankets northern Thailand in thick pollution. https://www.cnn.com/2023/04/05/asia/chiang-mai-air-pollution-thailand-intl-hnk/index.html

Cheng, D., Charles, A. C., Srigrarom, S., & Hesse, H. (2019). Morphing Concept for Multirotor UAVs Enabling Stability Augmentation and Multiple-Parcel Delivery. *AIAA Scitech 2019 Forum*. https://doi.org/10.2514/6.2019-1063

Chew, F., Gan, S., & Hesse, H. (2021). Rapid Design Process of Shrouded Rotors for Efficient UAV Propulsion. *AIAA Scitech 2021 Forum*. https://doi.org/10.2514/6.2021-0212

Cruz, R. (2025). Reforestation by Air: How Seed-Planting Drones Are Restoring Forests. https://advexure.com/blogs/news/reforestation-by-air-how-seed-planting-drones-are-restoring-forests

Dainelli, R., Toscano, P., Di Gennaro, S. F., & Matese, A. (2021). Recent Advances in Unmanned Aerial Vehicles Forest Remote Sensing—A Systematic Review. Part II: Research Applications. *Forests*, *12*(4), 397. https://doi.org/10.3390/f12040397

Elliott, S., Blakesley, D., & Hardwick, K. (2013). *Restoring Tropical Forests*. Kew Publishing.

Elliott, S., Gale, G., & Robertson, M. (2020). *Automated Forest Restoration: Could Robots Revive Rain Forests?* Chiang Mai, Forest Restoration Research Unit, Chiang Mai University.

Fukuoka, M. (2013). *Sowing Seeds in the Desert: Natural Farming, Global Restoration, and Ultimate Food Security*. Vermont, USA, Chelsea Green Publishing.

Goldapple, L. (2017). Drop seeds, not bombs. Aerial reforestation in Thailand. https://atlasofthefuture.org/project/aerial-reforestation-in-thailand/

Grossnickle, S. C., & Ivetić, V. (2017). Direct Seeding in Reforestation – A Field Performance Review. *REFORESTA*, (4), 94–142. https://doi.org/10.21750/REFOR.4.07.46

Holybro. (2025). Holybro X500 V2 Development Kit. https://holybro.com/collections/x500-kits/products/x500-v2-kits

Huang, X., Zhang, S., Luo, C., Li, W., & Liao, Y. (2020). Design and Experimentation of an Aerial Seeding System for Rapeseed Based on an Air-Assisted Centralized Metering Device and a Multi-Rotor Crop Protection UAV. *Applied Sciences*, *10*(24), 8854. https://doi.org/10.3390/app10248854

Javed, T., Afzal, I., Shabbir, R., Ikram, K., Saqlain Zaheer, M., Faheem, M., Haider Ali, H., & Iqbal, J. (2022). Seed coating technology: An innovative and sustainable approach for improving seed quality and crop performance. *Journal of the Saudi Society of Agricultural Sciences*, *21*(8), 536–545. https://doi.org/10.1016/j.jssas.2022.03.003

Karademir, S. (2025). Design and implementation of a novel seeding drone. *Sigma Journal of Engineering and Natural Sciences*, 189–198. https://doi.org/10.14744/sigma.2025.00014

Kaushikkar, A., & Whitman, J. (2023). Finding an optimized flight path for an UAV to seed a fire affected area. *Journal of Student Research*, *12*(1). https://doi.org/10.47611/jsrhs.v12i1.3866

Kim, J., Kim, S., Ju, C., & Son, H. I. (2019). Unmanned Aerial Vehicles in Agriculture: A Review of Perspective of Platform, Control, and Applications. *IEEE Access*, *7*, 105100–105115. https://doi.org/10.1109/ACCESS.2019.2932119

Kus, E. (2021). Seed Damage Test for Roller-Type Device Designed at Different Flute Helical Angles. *Uluslararası Tarım ve Yaban Hayatı Bilimleri Dergisi*, *7*(3), 495–502. https://doi.org/10.24180/ijaws.938870

Laohasom, P. (2024). *Restoring Bamboo-Deciduous Forest at Pong Yaeng Nork After Fire* (tech. rep.). Chiang Mai University. Chiang Mai. https://www.forru.org/projects/restoring-a-burnt-bamboo-deciduous-forest-at-pong-yaeng-nork

Liu, H., Chen, Z., Wang, Z., & Li, J. (2023). An Effective Precision Afforestation System for UAV. *Sustainability*, *15*(3), 2212. https://doi.org/10.3390/su15032212

Lu, Y., Ranjitkar, S., Harrison, R. D., Xu, J., Ou, X., Ma, X., & He, J. (2017). Selection of Native Tree Species for Subtropical Forest Restoration in Southwest China (B. Bond-Lamberty, Ed.). *PLOS ONE*, *12*(1). https://doi.org/10.1371/journal.pone.0170418

Lysych, M., Bukhtoyarov, L., & Druchinin, D. (2021). Design and Research Sowing Devices for Aerial Sowing of Forest Seeds with UAVs. *Inventions*, *6*(4), 83. https://doi.org/10.3390/inventions6040083

MissionPlanner. (2024). Mission Planner Home. https://ardupilot.org/planner/

Mohan, M., Richardson, G., Gopan, G., Aghai, M. M., Bajaj, S., Galgamuwa, G. A. P., Vastaranta, M., Arachchige, P. S. P., Amorós, L., Corte, A. P. D., de-Miguel, S., Leite, R. V., Kganyago, M., Broadbent, E. N., Doaemo, W., Shorab, M. A. B., & Cardil, A. (2021). UAV-Supported Forest Regeneration: Current Trends, Challenges and Implications. *Remote Sensing*, *13*(13), 2596. https://doi.org/10.3390/rs13132596

Naruangsri, K. (2023). *Developing Techniques for Direct Seeding for Forest Restoration in Northern Thailand* (Doctoral dissertation). Chiang Mai University. Chiang Mai. https://www.forru.org/library/0000282

Naruangsri, K., Pathom-aree, W., Elliott, S., & Tiansawat, P. (2024). Selecting Suitable Tree Species for Direct Seeding to Restore Forest Ecosystems in Northern Thailand. *Forests*, *15*(4), 674. https://doi.org/10.3390/f15040674

Naruangsri, K., Tiansawat, P., & Elliott, S. (2023). Differential seed removal, germination and seedling growth as determinants of species suitability for forest restoration by direct seeding – A case study from northern Thailand. *Forest Ecosystems*, *10*, 100133. https://doi.org/10.1016/j.fecs.2023.100133

Noble, F. (2020). Government set to revise total number of hectares destroyed during bushfire season to 17 million. https://www.9news.com.au/national/australian-bushfires-17-million-hectares-burnt-more-than-previously-thought/b8249781-5c86-4167-b191-b9f628bdd164

Nonko, E. (2023). Seed-Planting Drones Are Reforesting Canada With Lightning Speed. https://reasonstobecheerful.world/drone-tree-planting-reforesting-after-wildfires

Ong, Ang, H., Lian, E., Tan, T., Tan, K., Tay, E., Yau, P., Hesse, H., Woradit, K., & Bhatia, D. (2025). FIREfly Project: Forest Fire Monitoring and Prediction Using Machine Learning, In *International Conference on Artificial Intelligence and Machine Learning Research*, Singapore, SPIE. https://doi.org/10.1117/12.3056811

Ong, Srigrarom, S., & Hesse, H. (2019). Design Methodology for Heavy-Lift Unmanned Aerial Vehicles with Coaxial Rotors, In *AIAA Scitech 2019 Forum*, Reston, Virginia. https://doi.org/10.2514/6.2019-2095

Pixhawk. (2024). Pixhawk Open Hardware Project. https://github.com/pixhawk

Pugh, S. (1991). *Total Design*. Massachusetts, USA, Addison-Wesley Pub. Co.

Putra, H. M., Fikri, M. R., Riananda, D. P., Nugraha, G., Baidhowi, M. L., & Syah, R. A. (2020). Propulsion selection method using motor thrust table for optimum flight in multirotor aircraft. *AIP Conference Proceedings*, *2226*(1). https://doi.org/10.1063/5.0004809

Puttapirat, P., Woradit, K., Hesse, H., & Bhatia, D. (2024). FireFly Project: UAV Development for Distributed Sensing of Forest Fires, In *IEEE International Conference on Unmanned Aircraft Systems (ICUAS)*. https://doi.org/10.1109/ICUAS60882.2024.10556892

Song, C., Zhou, Z., Luo, X., Lan, Y., He, X., Ming, R., Li, K., & Gul Hassan, S. (2018). Design and test of centrifugal disc type sowing device for unmanned helicopter. *International Journal of Agricultural and Biological Engineering*, *11*(2), 55–61. https://doi.org/10.25165/j.ijabe.20181102.3757

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

Tamura, N., Lulow, M. E., Halsch, C. A., Major, M. R., Balazs, K. R., Austin, P., Huxman, T. E., & Kimball, S. (2017). Effectiveness of seed sowing techniques for sloped restoration sites. *Restoration Ecology*, *25*(6), 942–952. https://doi.org/10.1111/rec.12515

Taylor, J. B., Cass, K. L., Armond, D. N., Madsen, M. D., Pearson, D. E., & St. Clair, S. B. (2020). Deterring rodent seed-predation using seed-coating technologies. *Restoration Ecology*, *28*(4), 927–936. https://doi.org/10.1111/rec.13158

Tunjai, P. (2011). *Direct Seeding for Restoring Tropical Lowland Forest Ecosystems in Southern Thailand* (Doctoral dissertation). Walailak University. Thailand.

United Nations. (2021). United Nations Decade on Ecosystem Restoration (2021-2030). https://www.decadeonrestoration.org/

Velasquez-Camacho, L., Cardil, A., Mohan, M., Etxegarai, M., Anzaldi, G., & de-Miguel, S. (2021). Remotely Sensed Tree Characterization in Urban Areas: A Review. *Remote Sensing*, *13*(23), 4889. https://doi.org/10.3390/rs13234889

Waiboonya, P., & Elliott, S. (2020). Sowing time and direct seeding success of native tree species for restoring tropical forest ecosystems in northern Thailand. *New Forests*, *51*(1), 81–99. https://doi.org/10.1007/s11056-019-09720-1

Walker, A. (2021). 60 Years of Innovation: Exploring Tree Planting Drones to Make Australia Green Again! https://wwf.org.au/blogs/60-years-of-innovation-exploring-tree-planting-drones-to-make-australia-green-again

Woods, K., & Elliott, S. (2004). Direct seeding for forest restoration on abandoned agricultural land in northern Thailand. *Journal of Tropical Forest Science*, *16*(2), 248–259.

WWF. (2025). The Trillion Tree Initiative. https://trilliontrees.org/

Yuan, P., Yang, Y., Wei, Y., Zhang, W., & Ji, Y. (2024). Design and Experimentation of Rice Seedling Throwing Apparatus Mounted on Unmanned Aerial Vehicle. *Agriculture*, *14*(6), 847. https://doi.org/10.3390/agriculture14060847

Zhang, K., Khan, Z., Yu, Q., Qu, Z., Liu, J., Luo, T., Zhu, K., Bi, J., Hu, L., & Luo, L. (2022). Biochar Coating Is a Sustainable and Economical Approach to Promote Seed Coating Technology, Seed Germination, Plant Performance, and Soil Health. *Plants*, *11*(21), 2864. https://doi.org/10.3390/plants11212864

Zhang, X., Yang, Y., Wang, Q., Li, H., Zhang, Z., & Liu, J. (2023). Design and experiment of pneumatic seed clearing mechanism for pin-hole tube wheat plot precision sowing device. *International Journal of Agricultural and Biological Engineering*, *16*(4), 85–95. https://doi.org/10.25165/j.ijabe.20231604.8006

Zhong, W., Zhao, X., Liu, F., Bai, H., Dong, W., Hu, H., & Kong, X. (2024). Design and Experiment of Precision Seed Metering Device for Flow Adsorption of Quinoa Seeds. *Agriculture*, *14*(3), 434. https://doi.org/10.3390/agriculture14030434

Zhu, Y., Huang, X., Yin, C., Zhu, Q., Shi, Y., & Li, W. (2025). Key parameters determination based on seed movement process simulation for rice strip aerial seeding via UAV. *Computers and Electronics in Agriculture*, *237*, 110596. https://doi.org/10.1016/j.compag.2025.110596

Appendix A Lua Script for Limit Switch Operation

A Lua script has been implemented onboard the Pixhawk flight controller to continuously monitor the limit switch state for confirmation of successful seed drops, as described in Section 2.4.2. Figure 18 presents the logic of the limit switch operation.

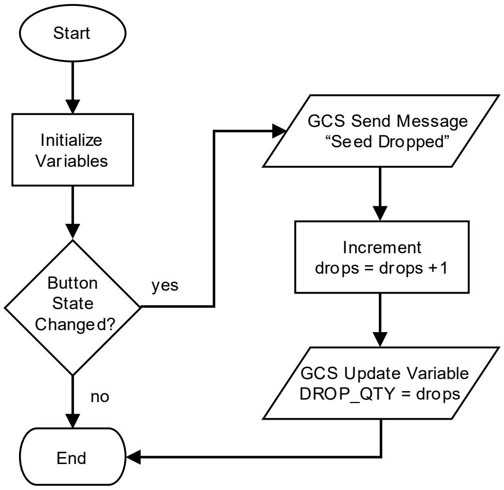


Figure 18: Flowchart of Lua script used for providing seed drop feedback.

The Lua script below has been uploaded to the Pixhawk flight controller. The script increments a drop counter each time a seed drop is detected.

```
local button_number = 1 -- The button number representing the limit switch
local button_active_state = true -- The ’pressed’ state of the limit switch
local last_button_state
local total_drops = -1 -- Initialize the counter for total seed drops

function update() -- this is the loop which periodically runs
    local button_new_state = button:get_button_state(button_number) == button_active_state
    -- checks for button press
    if button_new_state ˜= last_button_state then
        last_button_state = button_new_state
        if button_new_state then
            gcs:send_text(0, "Seed Drop Success") -- Send message to GCS
            gcs:send_named_float(’DROP_CNFRM’, 0)
            total_drops = total_drops + 1
            gcs:send_named_float(’DROP_QTY’, total_drops)
        else
            gcs:send_named_float(’DROP_CNFRM’, 1)
        end
    end
    return update, 0.1 -- updates the loop at 10Hz
end
return update() -- end of loop
```