Figure 2.1 – Photo from a UAV, of a forest restoration site, Ban Pong Krai, Chiang Mai Thailand. White dots in the image are ground markers (Photo by FORRU's DJI Phantom 4 Pro).

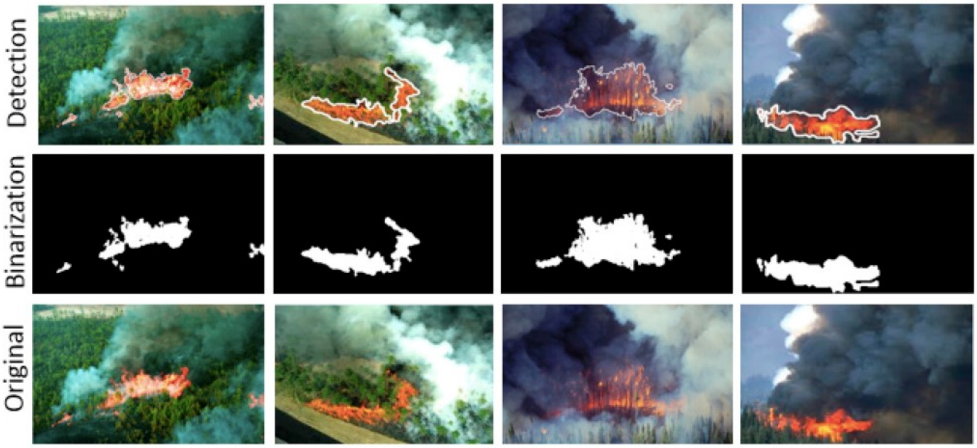

Figure 2.2 – Forest fire detections from UAVs (modified from Cruz et al., 2016)

UNMANNED AERIAL VEHICLES FOR AUTOMATED FOREST RESTORATION

***Pimonrat Tiansawat*[1] *& Stephen Elliott*[1]**

ABSTRACT

Unmanned aerial vehicles (UAVs) have been gaining in popularity and are used in many fields, including biodiversity conservation. They are currently available in many sizes and forms, and they can be used for aerial photography, mapping and monitoring natural resources. To use UAVs for automated forest restoration (AFR), technologies involved must be advanced and adapted, to perform the specific tasks required, particularly aerial seeding and maintenance procedures, such as weed control and fertilizer application. Getting UAVs to function fully autonomously, when performing such tasks, will be challenging. Integrative research, among engineers, computer scientists and ecologists, is needed to advance the AFR concept and the drone-based tools needed, to bring the concept to fruition.

Key words: drone, mapping, aerial seeding, aerial monitoring, power source, obstacle avoidance

INTRODUCTION

An unmanned aerial vehicle (UAV) is a flying device, with no pilot on board, which is controlled remotely, or flown autonomously, following a computer program. The basic components of UAVs include the body, computing components, a power supply, sensors that detect position and movement, software, flight controls, actuators, loop principles, a communications device and mounted payloads e.g. cameras n other sensors. Nowadays, several types of UAVs are available: rotary (multi- or single-) (Figs. 2.4 & 2.6), fixed-wing, and hybrids (Fig. 2.3). Each type is suited to perform specific functions. Although the first UAVs were pilotless planes, developed for military purposes, as early as 1900, modern UAVs have been used for various civilian applications, such as land-use planning, archaeological surveys, hobbies, and environmental and conservation tasks. In this review, we use the term UAV for the vehicles and UAV technologies to encompass ground control stations, communications and supporting equipment to operate flights.

---

[1] Forest Restoration Research Unit, Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand. Email: pimonrat.t@cmu.ac.th

The use of UAVs for automated forest restoration (AFR) is becoming more common among the research community. UAV technologies can be used to perform various tasks required to implement forest restoration, from site surveys (Fig. 2.1), to the development of restoration plans, site preparation, delivery of seeds and/or seedlings to the site, site management (i.e. weeding and fertilizing) and surveys for biodiversity recovery following restoration interventions (ELLIOTT, 2016) (Table 2.2). However, to achieve the goal of automated forest restoration, several specialized UAV technologies must be developed to perform specific tasks. Therefore, this chapter examines activities relevant to forestry applications, including those that are already achievable and those that might be achievable in the near future, and discusses challenges to developing UAVs for AFR.

CURRENT USE OF UAVs IN CONSERVATION

Forest mapping and monitoring

It has only been about two decades since UAVs gained attention in the forestry sector. The primary focus of UAV research has been on mapping and monitoring of forest stands (e.g. ABER et al., 1999 & 2002; DUNFORD et al., 2009; JAAKKOLA et al., 2010; SAARI et al., 2011; MAKYNEN et al., 2012; WALLACE et al., 2012; LISEIN et al., 2013; ZAHAWI et al., 2015; OTA et al., 2017) (Fig. 2.1). UAVs, have become ideal platforms to collect data and visual information from target areas using various payloads, including cameras and other sensors, Mapping and monitoring of forests normally require imaging sensors, a position sensor (i.e. Global Position System: GPS) and an Inertial Measurement Unit (IMU) (a combination of accelerometer, gyroscopes and sometimes a magnetometer).

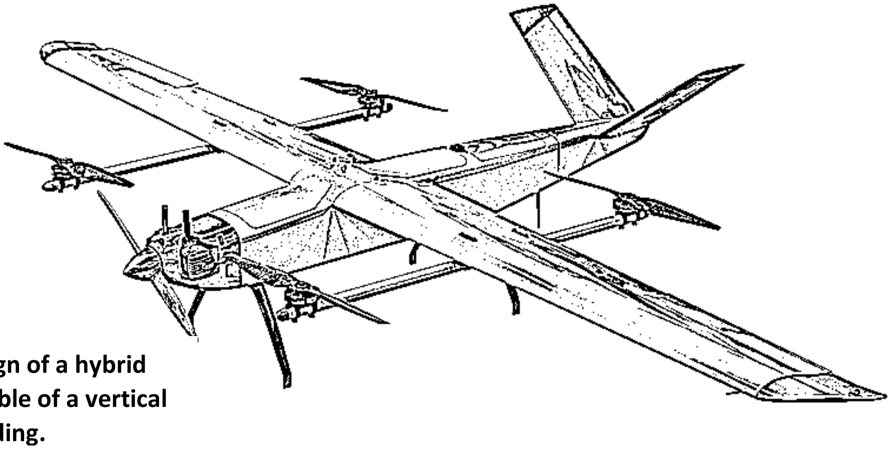

Figure 2.3 – design of a hybrid UAV that is capable of a vertical take-off and landing.

The most widely used imaging sensors are digital cameras sensitive to the visible spectrum (RBG cameras) (Fig. 2.1). HORCHER & VISSER (2004), pioneers in the use of small UAVs for forest imaging, reported that creating forest and stream maps with high-resolution images (8 cm per pixel) is possible using UAVs. Using more detailed and advanced mapping software, three-dimensional (3D) models of target areas can be constructed, using images and other data obtained from UAVs (REMONDINO et al., 2011). Additional sensors can be used, complementing or replacing RBG cameras, to acquire data for forest mapping such as: Light Detecting and Ranging (LiDAR) systems (also called laser scanners) (e.g. NAGAI et al., 2009; JAAKKOLA et al., 2010; WALLACE et al., 2012), multi- or hyper-spectral cameras (Fig. 2.4) and thermal sensors (e.g. BERNI et al., 2009; MAKYNEN et al., 2012; SMIGAJ et al., 2015).

The complementary data, acquired by such sensors, allows performance of more detailed analyses, to gain a more detailed understanding of forest structure. Investigations using such technologies have covered such broad topics as plant water-stress (ASNER et al., 2016), diseases (SMIGAJ et al., 2015), and other aspects of plant health (CALDERÓN et al., 2013). In addition to digital RBG images (Fig. 2.1), hyperspectral cameras (Fig. 2.4) can capture images using the near-infrared (NIR) spectrum. Combining data from the visible and near infrared spectra allows calculation of the Normalized Difference Vegetation Index (NDVI) and analyses of vegetation cover and health (LI et al., 2014). Chapter 3 provides more details about the uses of sensors for mapping and recognizing tree species.

Figure 2.4 - A UAV, equipped with hyper-spectral camera for research in Belgium (CARGYRAK, 2016)

With recent advances in positioning and imaging technologies, small UAVs are being used increasingly to map tree crowns and identify tree species (LISEIN et al., 2015; BAENA et al., 2017) (Fig. 2.7), estimate biomass (ENGLHART et al., 2013), map canopy gaps (GETZIN et al., 2014) and monitor fallen trees (INOUE et al., 2014) (Fig. 2.8).

Forest fire surveys

UAVs have also been used as sensor platforms to monitor forest fires (AMBROSIA et al, 2003; HINKLEY & ZAJKOWSKI, 2011; CRUZ et al., 2016) (Fig. 2.2), carrying either non-thermal infrared micro-cameras, imaging in the far infrared band (7-14 µm) (CASBEER et al., 2006; MERINO et al., 2012), or thermal infrared cameras, combined with IMUs and GPS collecting navigation and positioning data. Such UAVs usually send their data remotely, for immediate image processing at ground stations. Images are processed to minimize errors and to extract fire-contour information (fire perimeter) (Fig. 2.2). Data are fed into models to detect fires (CRUZ et al., 2016), predict their spread and plan appropriate fire-fighting options (MERINO et al., 2012). Single or multiple UAVs (cooperative) can be used to track the fires. Where fires become extensive, simultaneous deployment of multiple UAVs is needed, to update large amounts of information in near real-time (CASBEER et al., 2006).

Wildlife surveys

UAV technologies can also be used to detect wildlife habitats and estimate the abundance of wild animals and plot their distribution. Compared with satellite remote-sensing and ground surveys, the advantages of using UAVs include cloud-free images and lower cost (KOH & WICH, 2012). Moreover, aerial surveys by UAV can be conducted more frequently, to gather data for long-term monitoring. UAVs can be used both for taking photographs and for detecting radio-tagged animals. As camera platforms, they been successfully used to count and map the distribution of several large terrestrial animals (e.g. KOH & WICH 2012; VERMEULEN et al., 2013; BARASONA et al., 2014). VERMEULEN and his team (2013) used a fixed-wing drone, equipped with GPS, IMU and cameras to survey elephants (*Loxodonta africana*) in southern Burkina Faso (Fig. 2.5). The flight was fully autonomous and, at a height of 100 m, high enough for the elephants to appear unaware of the drone's presence. In Sumatra, Indonesia, a fixed wing drone successfully detected orangutans (*Pongo* spp.) and Sumatran elephants, flying 80-100 m above ground (KOH & WICH, 2012).

In addition to photography, UAVs can receive signals from animals that have been tagged with a radio transmitter (e.g. POSCH & SUKKARIEH, 2009). For example, a multi-rotor UAV, equipped with an antenna, was used to locate radio-tagged Noisy Miners (*Manorina melanocephala*) in Australia (CLIFF et al., 2015). The study showed that detection by UAV can be achieved both manually and autonomously. The main limitation of the technique was short flight time and inaccuracy, due to movements of birds (CLIFF et al., 2015). To mainstream UAV technologies for wildlife research, it is crucial to investigate the potential impacts of UAVs on target animals (e.g. DITMER et al., 2015).

UAV APPLICATIONS FOR AFR

To use UAVs to perform particular AFR tasks, task-specific hardware and software will be needed. Although currently available technologies, including imaging and positioning sensors, have allowed UAVs to perform rudimentary pre-restoration site surveys, locate seed trees (with partial success) and monitor some aspects of biodiversity recovery (large animals), a great deal of further research will be needed as well as development of a broader range of drone-mounted tools, if UAVs are to play a more universal and routine role in AFR. The need for three technologies immediately spring to mind: robot arms, guided by visual systems, capable of collecting seeds from tree crowns, seed delivery devices, capable of deploying seeds of multiple species of widely varying seed sizes, and "intelligent" spraying systems for weed control (Fig. 2.6). Although research is on-going, no working prototypes of these technologies currently exist.

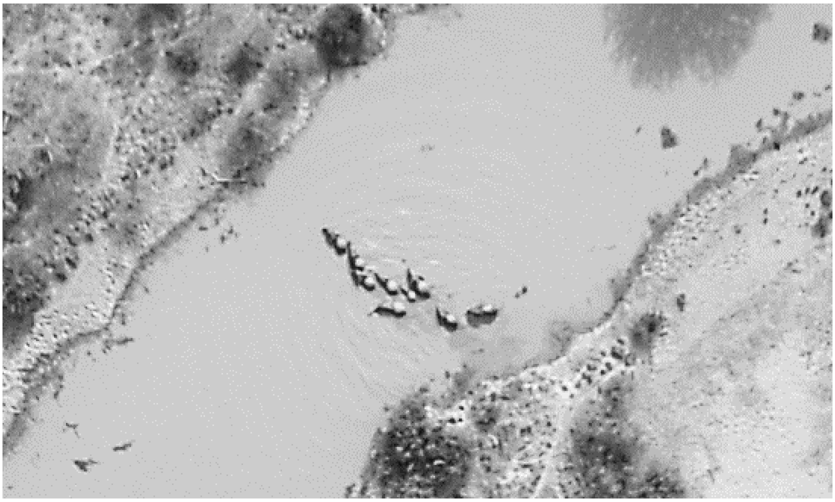

Figure 2.5 - Aerial image from a fixed-wing UAV, 300 m above ground, shows a group of elephants (modified from VERMEULEN et al., 2013).

Table 2.1 - AFR tasks and examples of task-specific hardware and software needs. *Italics* indicate items that will require more research and development.

AFR	Specific tasks	UAVs	
		Hardware	Software
Pre-site survey	Locating systems*	GPS, IMU unit	GPS software
	Imaging*	Cameras, other sensors	-
	Site evaluation – level of degradation	Cameras other sensors	*Databases and systems to process the images and decision making*
Seed collection	Locating seed trees	GPS, IMU unit	GPS software
	Plant recognition	Cameras, other sensors	*Databases and on-board processing*
	Seed collecting	*Robotic arms, cutting devices and seed storage*	*Systems to control the robotic arms (cutting mechanisms) and detecting the number of seeds UAVS can handle*
Seed delivery to target restored sites	Seed storage	*Seed containers*	-
	Aerial seeding	*Seed dropping device*	*Systems to control dropping patterns and to detect empty containers*
Fertilizer and/or herbicide application (maintenance)	Seedling recognition	Cameras, other sensors	*Databases and on-board real time processing and decision making*
	Fertilizer/herbicide application	*Containers for fertilizers/herbicides with appropriate application devices*	*Systems to make real-time on-board decisions, to control application patterns and to detect empty containers*

** All AFR tasks require location and imaging systems. Here, we include detection at the beginning and do not repeat for the rest of the table*

An overview of technologies already existing and required for further development is presented in Table 2.1. The size and weight of the drone-mounted tools will drive the development of new UAV designs to carry them and power-supply technologies, not only to fly the UAVs, but also to operate the attached devices for reasonable flight times. Site surveying and monitoring may not require large UAVs, because their main payloads will be cameras and sensors that have already been miniaturized. However, the robot arms, seed hoppers and tanks of fertilizer or herbicides are likely to be heavy and require large drones and power supplies well beyond the capacity of those currently in use.

Towards autonomy

Current UAV decision-making tools allow UAVs to fly autonomously only within predefined limited locations (ATHERTON, 2017). Many gaps in knowledge and technologies remain to be filled, before truly autonomous UAVs can be deployed to perform forest restoration tasks. Considerable improvements in power-supply systems, autonomous charging and advanced object-avoidance systems will be essential to enable UAVs to perform basic AFR tasks autonomously.

On-board power source

The power supply determines the flight time, and consequently the range, of UAVs. Typically, the power supply and fuel of large UAVs (>1,000 kg) constitute approximate 40-65% of their weight (NATIONAL RESEARCH COUNCIL, 2000). Smaller UAVs are powered by batteries, most commonly rechargeable lithium-ion polymer (LiPo) batteries. Therefore, the flight time and range of UAVs depends on battery capacity, discharge rate and average amp draw from the battery. LiPo batteries are favoured for UAVs, because of their thin shape and high discharge rates.

With current consumer-level battery technology, UAV flight times range from few minutes to 30 minutes (for 5-kg UAV). For AFR, particularly in remote large areas, much longer flight times will be needed, to make the use of drones practicable. This may be achieved by improving existing lithium-based technologies, but more likely, it will involve development of new power-supply systems. For example, prototype hydrogen fuel-cells have been used to successfully power UAVs for several hours (SWIDER-LYONS, 2016). Moreover, fuel-cell powered UAVs are quieter than those powered by regular batteries; they vibrate less during flight, are easier to control and have net zero emissions (SWIDER-LYONS et al., 2013). In 2004, The Naval Research Laboratory (NRL) of the United States of America successfully flew a hydrogen-fuel-cell-remote-piloted UAV for three hours and 19 minutes (flight weight 1.7 kg) (STROMAN et al., 2006): a record beaten recently by a team in China[2] who achieved a flight time of >5 hours.

Wireless charging

If LiPo batteries, with their relatively short flight times, remain the most affordable UAV power source, then automated wireless charging could be a way to maintain drone flights for AFR tasks in remote areas. Several companies are working on this, with varied approaches.

Charging pads have already been developed for small UAVs (e.g. SKYSENSE INC.). Skysense INC's charging system consists of a rugged, weather-resistant, stainless steel plate, on which UAVs land. UAVs are retrofitted with charging devices on the legs. These transfer charge to the batteries, as soon as the charging devices come into contact with the steel plate. Charging proceeds automatically, regardless of position, dimension and orientation of the drone[3].

Another technique, being explored, is magnetic resonance (JUNG et al., 2012; KESLER, 2016; SOLACE POWER INC., 2017). A UAV (the receiver) and a charging station (the energy source) are both equipped with copper coils. Once a UAV lands on or hoovers above the landing pad, the coils in the landing pad are turned on. An added feature of the station would be robotic arms to help align the UAV coils with the pad's coils. When the coils attached to the UAV are close enough to the pad's coils, a magnetic field is created and the UAV's battery is charged through electromagnetic induction. After charging is complete, the UAV signals the landing station to cease charging, and the drone can fly away and continue working.

The use of high-power lasers, to charge UAVs, is also being investigated (POWERLIGHT TECHONOLOGIES INC., 2017). With this method, UAVs are fitted with photovoltaic (PV) receivers. The UAVs hover over charging stations, where they are precisely aligned automatically using laser-tracking systems. The charging laser is then aimed at the PV receiver, where laser energy is used to charge the battery, while the UAV continues to hover. The ability to charge drones without landing them is obviously advantageous, where vegetation might obstruct safe landing. One limitation of this method is its high cost; high-power lasers are currently very expensive. However, as with other new technologies, costs are expected to fall, as the technology evolves for commercial use (POWERLIGHT TECHNOLOGIES INC., 2017).

---

[2] https://www.intelligentliving.co/hydrogen-fuel-drone/

[3] https://skycharge.de/charging-pad-outdoor

Another approach is to build ground stations, equipped with robotic arms, capable of swapping batteries. An Israeli company, named Airobotics, has developed a ground station with this battery-swap approach (AIROBOTICS, 2018). The system includes a 45-kg box that can be opened at the top. The UAV and ground station are equipped with sensors and communicate with each other. The UAV is also equipped with GPS, cameras, and sonar sensors for navigation and landing on the ground station. The ground station can help guide the landing, using its sensors and a radio signal. Upon landing, a robotic arm replaces the discharged battery with a fully charged one. Up to 10 batteries can be stored in each ground station.

However, all these technologies require power, and in remote areas, where forest restoration is most likely to occur, there is usually no mains electricity. Therefore, in the context of AFR, all these charging stations are most likely to be run on solar power; solar panels feeding electricity into large on-site batteries. Once set up, solar power systems require little maintenance. Therefore, they are the most promising power source to drive autonomous AFR systems.

Powering UAVs directly by on-board solar energy has also been attempted, but not very successfully as yet. Titan Aerospace developed a prototype, solar-powered, fixed-wing UAV in 2015, design for sustained, high-altitude flight, to deliver internet connectivity over wide areas. At 15 m in length and with a wing-span of 50 m, it was anticipated that the Solara 50 would carry payloads of up to 32-kilogram and be capable of continuous flights lasting up to five years. The first and only flight of the Solara 50 was in 2015 in New Mexico, USA. Unfortunately, the left wing suffered a structural failure, shortly after take-off, and the vehicle crashed (NATIONAL TRANSPORTATION SAFETY BOARD, 2015). The project was subsequently shelved.

Using multiple UAVs for forest restoration tasks

As already stated above and summarized in Table 2.1, various, highly specialized, drone-mounted tools will be required to perform the various tasks that comprise an AFR project from start to finish, from robot arms to collect seeds, to herbicide spraying devices. This gives rise to two approaches to drone development for AFR: the generalist or specialist approaches.

The first would entail development of UAVs that are capable of performing several different tasks ("Jack-of-all-trades UAVs"). Generalist UAVs would be capable of carrying various interchangeable tools, attached by a universal docking system. The docking system would have to transmit power from the UAV power supply to the attached tool and enable data exchange between the UAV and the tool, so that UAV flight-control systems could maintain stability, in response to the tools' movements or status. A potential disadvantage of this approach might be that human operators would be needed to interchange the attachments and carry out safety tests. Thus, complete autonomy might be sacrificed. However, the generalist approach is likely to be cost-effective, since mass production of the basic UAVs could be performed with economies of scale, whilst design of specialized tools can continue independently, provided a standard docking system is used.

The second approach is to design individual UAVs, each with an integrated tool, to perform one specific task ("specialist UAVs"). This would enable better integration of the tool with the flight systems and remove the possibility of docking-system failure. However, it would be wasteful and therefore more expensive, since drones would be idle when the task, for which they were designed, is not being performed.

Depending on a project's specific needs and constraints, either approach may be appropriate. Labour costs and the costs for developing technologies vary across different parts of the world. Hopefully as the use of UAVs for AFR spreads, the associated costs will come down, as new technologies become more readily available.

Figure 2.6 - A multi-rotor UAV, equipped with a liquid-storage and spraying system (Photo by Stephen Elliott)

Another consideration when using UAVs for AFR is controlling UAV swarms. Performing AFR on areas larger than a few hectares will require co-ordination of multiple drones, perhaps simultaneously performing different tasks, without impinging upon each other's airspace, and without interfering with performance of their programmed tasks. This will require UAVs to communicate with each other, in real time, and adjust their flight paths and operations, in response to the position of every other drone in the area, whilst all UAVs work towards a shared universal objective.

Advances in programming of drone swarms have been considerable in recent years (e.g. ABATTI, 2005; BRUST & STRIMBU, 2016; CONDLIFF 2017; MEHTA 2017; KUMAR 2017), particularly for military purposes, such as intelligence and surveillance (ABATTI, 2005; MEHTA 2017) and for creating spectacular lights shows as large open-air public events. For swarm UAVs, the size of each individual in the swarm is small, and one swarm may consist of 100 of individuals (CONDLIFFE, 2017; MEHTA 2017).

By recognizing various approaches for UAV development, it is important for technologists and forest practitioners to work together at the early stages of development.

CONCLUSION

Restoration of diverse forest ecosystems is one of the most important tasks to mitigate global climate change. In the last few decades, we have gained more knowledge about forest restoration, whilst engineers have also developed UAV technologies, capable of many practical applications relevant to the task. This review has discussed the current use of UAVs in forestry and conservation, and looks forward to greater use of those technologies in forest restoration, gradually achieving increased autonomy, as improved technologies become more readily available and more cost-effective (Table 2.2).

UAV technologies can be applied to all aspects of forest restoration, from project planning to monitoring and assessment of project achievements, in terms of biomass accumulation, recovery of forest structure and biodiversity and the ultimate goal of returning ecological functioning. The time is ripe for a cross-disciplinary effort to develop and implement these technologies. The integration of engineering and restoration ecology is the hope for our future.

REFERENCES

ABATTI, J. M., 2005. Small Power: The Role of Micro and Small UAVs in the Future. Center for Strategy and Technology Air War College, Air University. Alabama, USA.

ABER, J. S., R. J. SOBIESKI, D.A. DISTLER, & M.C. NOWAK, 1999. Kite aerial photography for environmental site investigations in Kansas. Trans. Kans. Acad. Sci. 102: 57-67.

ABER, J.S., S.W. ABER, & F. PAVRI. 2002, Unmanned small format aerial photography from kites acquiring large-scale, high-resolution, multiview-angle imagery. *Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS 2002*, Denver, Colorado, US, November 8-15, 2002;

AIROBOTICS, 2018. Airobotic Solutions. (Accessed 17 July 2018). Available from: https://www.airoboticsdrones.com/

AMBROSIA, V. G., S. S. WEGENER, D. V. SULLIVAN, S. W. BUECHEL, D. E. DUNAGAN, J. A. BRASS, J. STONEBURNER, & S. M. SCHOENUNG, 2003, Demonstrating UAV-acquired real-time thermal data over fires. Photogramm. Eng. Remote Sensing 69: 391-402.

ASNER, G. P., P. G., BRODRICK, C. B.,ANDERSON, N., VAUGHN, D. E., KNAPP & R. E. MARTIN, 2016. Progressive forest canopy water loss during the 2012–2015 California drought. PNAS 113 (2): E249-E255.

ATHERTON, K. D., 2017. The Pentagon's new drone swarm heralds a future of autonomous war machines. (Accessed 17 January, 2017). Available from: http://www.popsci.com/pentagon-drone-swarm-autonomous-war-machines.

BAENA, S., J. MOAT, O. WHALEY, & D.S. BOYD, 2017. Identifying species from the air: UAVs and the very high resolution challenge for plant conservation. PLOS ONE 12(11): E0188714.

BARASONA, J. A., M. MULERO-PAZMANY, P. ACEVEDO, J. J. NEGRO, M. J. TORRES, C. GORTAZAR, & J. VICENTE, 2014. Unmanned aircraft systems for studying spatial abundance of ungulates: relevance to spatial epidemiology. PLOS ONE 9(12): e115608.

BERNI, J. P. ZARCO-TEJADA, L. SUÁREZ,V. GONZÁLEZ-DUGO, & E. FERERES, 2009. Remote sensing of vegetation from UAV platforms using lightweight multispectral and thermal imaging sensors. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 38: 6.

BRUST, M.R., & B.M. STRIMBU, 2015. A networked swarm model for UAV deployment in the assessment of forest environments. P. 1-6 in *2015* IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks & Information Processing (ISSNIP)

CALDERÓN, R. J. NAVAS-CORTÉS, C. LUCENA & P. 0ZARCO-TEJADA, 2013. High-resolution airborne hyperspectral and thermal imagery for early detection of *Verticillium* wilt of olive using fluorescence, temperature and narrow-band spectral indices. Remote Sens. Environ. 139: 231–245.

CARGYRAK, 2016. Onyxstar_HYDRA12_UAV_with_embedded_hyperspectral_camera _for_ agricultural_research.jpg. in Wikimedia Commons [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]

CASBEER, D. W., D. B. KINGSTON, R. W. BEARD, & T. W. MCLAIN, 2006. Cooperative forest fire surveillance using a team of small unmanned air vehicles. Int. J. Syst. Sci. 37: 351-360.

CLIFF, O.M., R. FITCH, S. SUKKARIEH, D.L. SAUNDERS, & R. HEINSOHN, 2015. Online localization of radio-tagged wildlife with an autonomous aerial robot system. Robotics: Science & Systems. MIT Press Journals.

CONDLIFFE, J., 2017. A 100-Drone Swarm, Dropped from Jets, Plans Its Own Moves. (Accessed 24 July, 2017). Available from: https://www.technologyreview.com /s/603337/ a-100-drone-swarm-dropped-from-jets-plans-its-own-moves/.

CRUZ, H., M. ECKERT, J. MENESES & J. F. MARTÍNEZ, 2016. Efficient Forest Fire Detection Index for Application in Unmanned Aerial Systems (UASs). Sensors. 16 (6): 893.

DITMER, M.A. J. B. VINCENT, L. K. WERDEN, J. C. TANNER, T. G. LASKE, P. A. IAIZZO, D. L. GARSHELIS, & J. R. FIEBERG, 2015. Bears show a physiological but limited behavioral response to unmanned aerial vehicles. Curr. Biol. 25: 2278-2283.

DUNFORD, R., K. MICHEL, M. GAGNAGE, H. PIÉGAY & M. L, TRÉMELO, 2009. Potential and constraints of Unmanned Aerial Vehicle technology for the characterization of Mediterranean riparian forest. *Int. J. Remote Sens.* 30 (19): 4915-4935.

ELLIOTT, S, 2016. The potential for automating assisted natural regeneration of tropical forest ecosystems. Biotropica. 48(6): 825-833.

ENGLHART, S., J. JUBANSKI & F. SIEGERT, 2013. Quantifying Dynamics in Tropical Peat Swamp Forest Biomass with Multi-Temporal LiDAR Datasets. Remote Sens. 5 (5): 2368.

GETZIN, S., R. NUSKE & K. WIEGAND, 2014. Using Unmanned Aerial Vehicles (UAV) to Quantify Spatial Gap Patterns in Forests. Remote Sens. 6 (8): 6988.

HINKLEY, E. A., T. ZAJKOWSKI, 2011. USDA forest service–NASA: Unmanned aerial systems demonstrations – pushing the leading edge in fire mapping. Geocarto Int. 26: 103-111.

HORCHER, A., R.J. VISSER, 2004. Unmanned aerial vehicles: Applications for natural resource management and monitoring, Council on Forest Engineering Proceedings 2004: Machines & People, The Interface.

INOUE, T., S. NAGAI, S. YAMASHITA, H. FADAEI, R. ISHII, K. OKABE, H. TAKI, Y. HONDA, K. KAJIWARA, & R. SUZUKI, 2014. Unmanned Aerial Survey of Fallen Trees in a Deciduous Broadleaved Forest in Eastern Japan. PLOS ONE 9(10): E109881.

JAAKKOLA, A., J. HYYPPÄ, A. KUKKO, X. YU, H. KAARTINEN, M. LEHTOMÄKI, *et al.,* 2010. A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. ISPRS J. Photogramm. Remote Sens. 65 (6): 514-522.

JUNG, S., T. LEE, T. MINA & K. B. ARIYUR, 2012. Inductive or Magnetic Recharging for Small UAVs. SAE 2012 Aerospace Electronics & Avionics Systems Conference.

KESLER, M, 2016. Highly Resonant Wireless Power Transfer: Safe, Efficient, and over Distance. WiTricity Corporation. Available from: http://witricity.com/wp-content/uploads/2016/12/White_Paper_ 20161218.pdf.

KOH, L. P., & S. A. WICH, 2012. Dawn of drone ecology: Low-cost autonomous aerial vehicles for conservation. Trop. Conserv. Sci. 5: 121-132.

KUMAR, V., 2017. Current Projects: Vijay Kumar Lab. (Accessed 24 July, 2017). Available from: https://www.kumarrobotics.org/research/.

LI, L., Q. ZHANG, & D. HUANG, 2014. A Review of Imaging Techniques for Plant Phenotyping. Sensors 14(11):20078.

LISEIN, J., M. PIERROT-DESEILLIGNY, S. BONNET, & P. LEJEUNE, 2013. A photogrammetric workflow for the creation of a forest canopy height model from small unmanned aerial system imagery. Forests 4: 922-944.

LISEIN, J., A. MICHEZ, H. CLAESSENS, & P. LEJEUNE, 2015. Discrimination of Deciduous Tree Species from Time Series of Unmanned Aerial System Imagery. PLOS ONE 10(11):E0141006.

MAKYNEN, J., H. SAARI, C. HOLMLUND, R. MANNILA, & T. ANTILA, 2012. Multi- and hyperspectral UAV imaging system for forest and agriculture applications. In Next-generation spectroscopic technologies v, Druy, M.A.; Crocombe, R.A., Eds. 2012; Vol. 8374.

MEHTA, A, 2017. DoD weapons designer: Swarming teams of drones will dominate future wars. Defense News. (Accessed 17 July 2018). Available from: https://www.defensenews.com/smr/unmanned-unleashed/2017/03/30/dod-weapons-designer-swarming-teams-of-drones-will-dominate-future-wars/.

MERINO, L., F. CABALLERO, J. RAMIRO MARTINEZ-DE-DIOS, I. MAZA, & A. OLLERO, 2012. An unmanned aircraft system for automatic forest fire monitoring and measurement. J. Intell. Robot. Syst. 65: 533-548.

NAGAI, M., R. SHIBASAKI, H. KUMAGAI & A. AHMED, 2009. UAV-borne 3-D mapping system by multisensor integration. IEEE Trans. Geosci. Remote Sens. 47: 701–708.

NATIONAL RESEARCH COUNCIL, 2000. *Uninhabited Air Vehicles: Enabling Science for Military Systems*. The National Academies Press: Washington, DC, 124 p.

NATIONAL TRANSPORTATION SAFETY BOARD, 2015 Aviation Accident Final Report DCA15CA117. May 2015 Aviation Accidents.

OTA, T., M. OGAWA, N. MIZOUE, K. FUKUMOTO, & S. YOSHIDA, 2017. Forest Structure Estimation from a UAV-Based Photogrammetric Point Cloud in Managed Temperate Coniferous Forests. Forests 8(9):343.

POSCH, A., & S. SUKKARIEH, 2009. UAV based search for a radio tagged animal using particle filters. 2009 Australasian Conference on Robotics & Automation, 2–4 December 2009, Sydney, Australia.

POWERLIGHT TECHONOLOGIES, 2017. Free-space power beaming. (Accessed 17 July 2018). Available from: https://powerlighttech.com/free-space-power-beaming-2/

REMONDINO, F., L. BARAZZETTI, F. NEX, M. SCAIONI, & D. SARAZZI, 2011. UAV photogrammetry for mapping and 3D modeling-Current status and future perspectives. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 38. DOI: 10.5194/isprsarchives-XXXVIII-1-C22-25-2011.

SAARI, H., I. PELLIKKA, L. PESONEN, S. TUOMINEN, J. HEIKKILÄ, C. HOLMLUND, J. MÄKYNEN, K. OJALA & T. ANTILA, 2011. Unmanned aerial vehicle (UAV) operated spectral camera system for forest and agriculture applications, Proc. SPIE. 81740H.

SMIGAJ, M., R. GAULTON, S. L. BARR, & J. C. SUÁREZ, 2015. UAV-borne thermal imaging for forest health monitoring: detection of disease-induced canopy temperature increase. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XL-3/W3 349-354.

SOLACE POWER INC., 2017. Solace technology. (Accessed 24 July, 2017). Available from: https://www. solace.ca /technology/.

STROMAN, R., J. C. KELLOGG, & K. SWIDER-LYONS, 2006. Testing of a PEM fuel cell system for small UAV propulsion, 487-490 p.

SWIDER-LYONS, K., R. O. STROMAN, RODGERS, J. A., D. EDWARDS, J. A. MACKRELL, M. W. SCHUETTE, G. S. PAGE, 2013. Liquid hydrogen fuel system for small unmanned air vehicles. Proceedings of 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum & Aerospace Exposition 2013, AIAA, Grapevine, TX.

SWIDER-LYONS, K., 2016. Hydrogen fuel cells for small unmanned air vehicles. DOE webinar. 26 May 2016.

VERMEULEN, C., P. LEJEUNE, J. LISEIN, P. SAWADOGO & P. BOUCHE, 2013. Unmanned Aerial Survey of Elephants. PLOS ONE 8: e54700.

WALLACE, L., A. LUCIEER, C. WATSON & D. TURNER, 2012. Development of a UAV-LiDAR system with application to forest inventory. Remote Sens. 4: 1519-1543.

ZAHAWI, R.A., J. P. DANDOIS, K. D. HOLL, D. NADWODNY, J. L. REID, & E. C. ELLIS, 2015. Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. Biol. Conserv. 186: 287-295

Table 2.2 – Idealized auto-restoration work flow and required technologies, showing how the need for human inputs could potentially be minimized

TECH NEEDED	TASK	OUTPUT
Human intervention	Establish ground station	Power supply, stocks of herbicide & fertilizer
UAVs, cameras, tree-identification software	Survey nearby target forest remnant	Set restoration goals – locate seed sources
UAVs, cameras, restoration planning software	Survey restoration site	Restoration plan – seed requirements calculated
UAVs, seed collection devices & controlling software	Seed collection	Seeds
Human intervention	Process seeds & prepare them for delivery	Seed bombs
UAVs with seed-dropping devices	Aerial seeding	Restoration site seeded with trees
UAVs + spraying devices for herbicide and liquid fertilizer	Maintenance	Tree seedlings protected from weeds and supplied with nutrients
UAVs + cameras, tree identification software – thermal cameras for animals	Monitoring vegetation and animals	Data: tree survival, growth & biomass; recovery of forest structure & faunal recolonization
REPEAT	Move ground station to new restoration site	Restoration objectives achieved

Figure 2.7 - Raw UAV-borne-compact-camera image showing two tree crowns (birch and poplar species) with different spectral signatures (modified from Lisein et al., 2015)

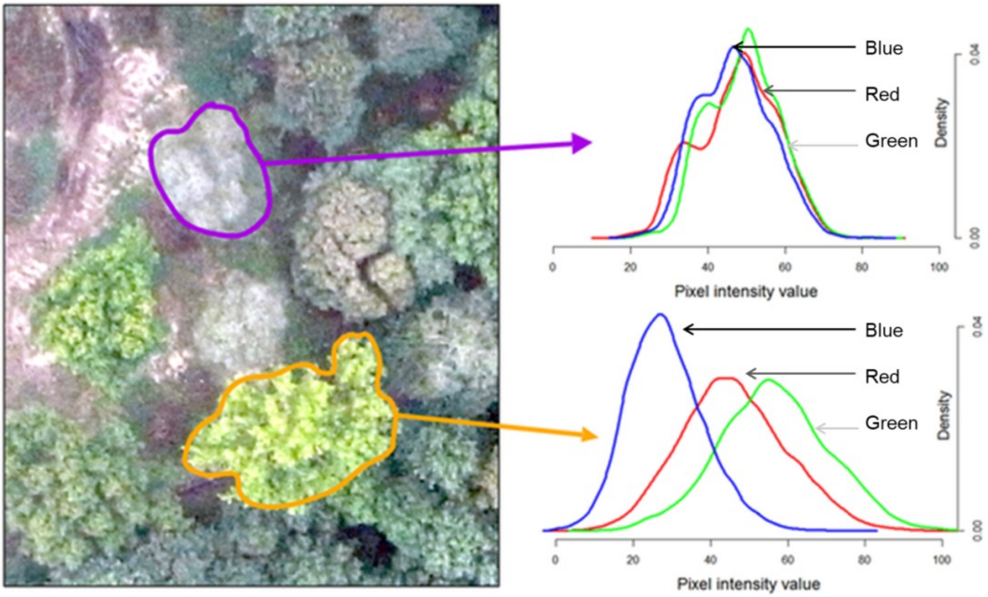

Figure 2.8 Views of the same point from different angles for detecting fallen trees (arrows). Nadir looking image detects three fallen trees hidden by standing trees (boxes) (reprinted from Inoue et al., 2014)