Remote sensing for precision forestry

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Abstract

This article summarises recent developments in remote sensing technologies that will have, or are already having, a substantial impact on forest management practices. These technologies have the potential to usher in a new era for the forestry sector with the advent of precision forestry. In this article we review forest measurement through laser scanning, satellite imagery for forest management and developments in the field of unmanned aerial vehicles.

Introduction

The abundant data produced by remote sensing systems has had a substantial impact on the understanding and management of forests across the planet. Over the past 50 years, the development of remote sensing technologies has accelerated and several are now routinely used as part of forest management practices. The exponential growth of sensor technology – ever smaller, lighter, faster and cheaper – is responsible for a growing inundation of data. The remote sensing revolution brings the potential to change the spatial and temporal resolution of the information we use to manage our forests. This detailed data, and the associated analytical tools, are the key enabling technologies in the development of precision forestry. The challenge facing forestry researchers is the development of methods to extract information relevant for forest management from the growing mass of data. With the development of appropriate tools the impact that remote sensing will have on forest management over the next 50 years will be profound.

What is precision forestry?

Precision forestry is a term adapted from the agricultural sciences, where for some years ‘precision agriculture’ has been used to describe the application of modern electronics, computers and sensors to agriculture and its related disciplines. The term ‘precision forestry’, coined relatively recently, refers to the use of high-tech sensors and analytical tools to support site-specific forest management. There are a multitude of definitions and applications of the term, but a useful summary comes from the opening remarks to the inaugural Symposium on Precision Forestry (2001) by Professor B. Bruce Bare of the University of Washington:

> *The goal of precision forestry is to deploy high-resolution data to support site-specific tactical and operational decision-making. This allows for highly repeatable measurements, actions and processes to grow and harvest trees, as well as to protect and enhance riparian zones, wildlife habitat, aesthetics, and other environmental resources.*

Whichever definition you prefer it is clear that precision forestry is supported by a range of sensor technologies that can be used to generate detailed and timely information about forests.

Since the advent of the application of aerial photography to forest inventory in the 1950s, remote sensing has supported forest measurement and forest management (McRoberts et al., 2010). Precision forestry furthers this tradition through the development and application of technologies that provide detail on our forests, and the environments they inhabit, along with mechanisms to store and analyse the newly available data to create relevant information and knowledge.

Research and development of precision forestry tools constitute a significant component of Growing Confidence in Forestry’s Future (GCFF), a major six-year research programme involving Scion and its partners and jointly funded by the New Zealand Forest Growers Levy Trust and the Ministry for Business Innovation and Employment (www.gcff.nz). The objective of GCFF is to improve the productivity, profitability and sustainability of New Zealand’s commercial forestry investments and the tools of precision forestry are a key enabler for this endeavour.

The purpose of this article is to inform readers about developments in the application of remote sensing research that are available, or relevant, to New Zealand’s forest managers. Furthermore we hope to challenge forest managers to think about how these tools can be integrated into current systems to innovate and improve forest management. Our objective is not to provide a comprehensive review, but to provide a summary of some of the technologies relevant to the New Zealand industry and, where appropriate, highlight recent research activities.

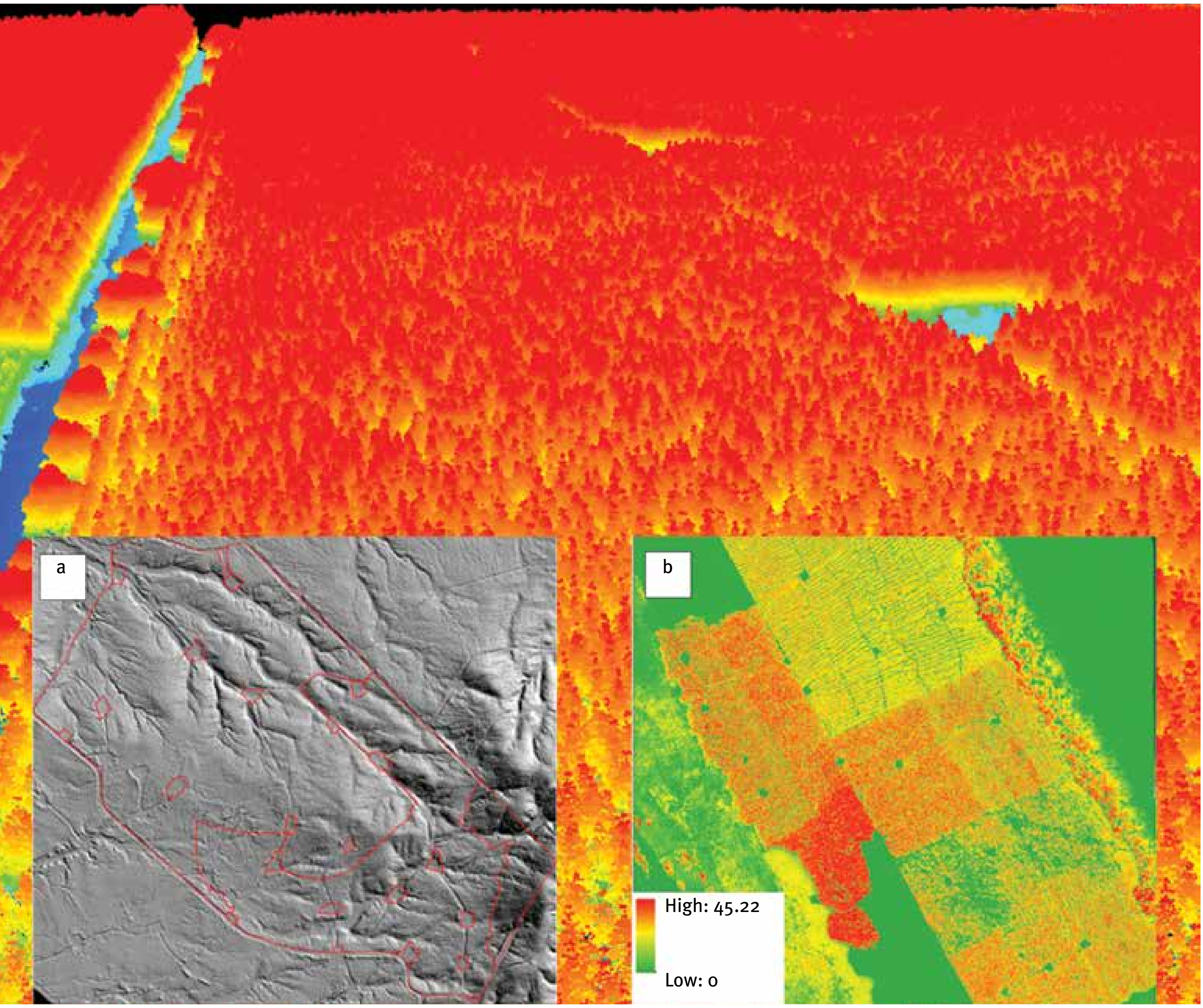

Figure 1: An ALS point cloud collected over a radiata plantation (background) with representations of two processing outputs: a) a digital terrain model (DTM); and b) a canopy height model (CHM)

Airborne laser scanning (ALS)

No single innovation has advanced the progress of precision forestry more than the advent of airborne laser scanning (ALS) and the development of techniques for its application to forest resource assessment. ALS systems are active remote sensing systems that make use of light detection and ranging (LiDAR) technology and typically consist of a laser scanner and sensor mounted in an aircraft. ALS systems are commonly characterised by the type of information they record as either discrete, where the profile of the back-scattered light from the emitted laser pulse is discretised into 'returns' when the intensity of energy returned to the sensor is above a pre-defined threshold, or full waveform where the entire profile of the returned pulse is recorded.

The vast majority of ALS systems in use globally for vegetation and terrain mapping collect discrete data, and the remainder of this article will discuss discrete ALS. These systems use narrow pulses of near-infrared (1064 nm) light emitted by the scanner at a very high frequency, typically around 200,000 pulses per second. The back-scattering of these pulses by the objects they encounter is recorded by the sensor aboard the aircraft. Through accurate measurement of the time elapsed between emission and return of a pulse to the sensor the distance, or range, of the target object from the sensor can be calculated because the speed of light is constant. An inertial measurement unit (IMU) and global position system (GPS) on board the aircraft are the two final pieces of the puzzle that provide exact positional information and allow each return to be converted into an x, y, z coordinate.

The resulting data set of dense positional information on the distant target is referred to as a point cloud (Figure 1). With up to 200,000 pulses per second emitted, and up to five discrete returns per pulse recorded, ALS derived point clouds provide an exceptionally detailed 3D representation of the vegetation structure and the terrain below it. A proportion of the emitted laser pulses penetrates all vegetation and is reflected to the sensor from the ground below. Once separated from the vegetation returns the ground points can be used to produce a digital terrain model (DTM) usually via triangulation. These models provide the most detailed description of the forest floor available resulting in useful information on slope, aspect and hydrological conditions, helping us build an understanding of the growing conditions experienced by our trees.

Once the bare earth returns are removed a DTM can be used to convert the z coordinates of the vegetation point clouds into locally normalised heights. The above-ground point cloud can then be used to produce a canopy height model (CHM), and interrogated to produce meaningful metrics that contain useful information about forest and tree structure. Coupled with ground-plot measurements, these metrics can greatly improve the detail and quality of resource description. Studies into ALS are commonly split between those that characterise the forest at a patch level, usually referred to as area-based analysis (ABA), and those that are concerned with individual tree analysis (ITA).

Area-based analysis (ABA)

Since the earliest applications of laser scanning to assist forest measurement (Maclean and Krabill, 1986) the technology has been widely applied, predominantly through ABA, to spatially characterise the variation in stand structure. The development of techniques that use the auxiliary data available from ALS were pioneered by researchers in the Nordic countries and the same groups still provide cutting edge research in this area. Their results consistently demonstrated the marked precision improvements available when using ALS compared to conventional forest inventories and led to the uptake of techniques that have become standard practice for forest measurement across Scandinavia (Naesset, 2007). In addition to conventional stand attributes, such as merchantable volume, ABA techniques have been extended to provide useful information on a myriad of other attributes including biomass (Gobakken et al., 2012), fire risk (Chen et al., 2014), leaf-area index (LAI) (Tang et al., 2014) and biodiversity (Hill and Broughton, 2009).

The first application of ABA in New Zealand was as part of the planted forest component of an innovative national carbon inventory commissioned by the Ministry for the Environment. The inventory approach successfully used double sampling to improve inventory precision (Stephens et al., 2012). Funded through the Future Forest Research programme, researchers at Scion developed practical guidance for the acquisition and use of ALS in New Zealand conditions (Adams et al., 2011; Adams and Pont, 2012; Watt et al., 2013a; Watt et al., 2013b; Watt et al., 2013c; Watt and Watt, 2013; Watt et al., 2014). This work generated considerable interest from the industry who supported further research into suitable ABA techniques that could meet their specific forest inventory demands (Dash et al., 2015a).

In recent years, non-parametric modelling methods such as k-nearest neighbour (k-NN) have become exceptionally popular for predicting stand attributes using remotely sensed data. First applied to forestry in Finland in the 1990s, the k-NN technique is particularly compatible with the demands of New Zealand's commercial forestry sector. This is due to numerous factors including: 1) a requirement for simultaneous prediction of a multitude of correlated log-product volumes to produce yield outputs that are additive and consistent; 2) a desire for flexibility so that new log-products or harvest plans can be introduced without the need for model redevelopment; and 3) the ability to integrate pre-existing biometric models and software with data from remote sensing without major disruption.

A collaboration between Scion (then called FRI) and their Finnish counterparts Metla (Tomppo et al., 1999) provided the first trials of k-NN for forest inventory in New Zealand using satellite imagery to provide auxiliary resource data. Despite showing promise, the approach could not be used to predict log-product volumes with sufficient accuracy due, in part, to spectral saturation in New Zealand's highly productive plantations. Some years later Dash et al. (2015a) showed that, when applied to ALS data, k-NN can meet New Zealand's data requirements and provide accurate and consistent maps of forest attributes. These maps can be used to generate yields for any stand, or other area of interest, covered by the ALS campaign with a high degree of accuracy. The k-NN approach is compatible with current yield prediction systems and requires considerably fewer field plots than a conventional inventory approach to achieve similar levels of precision. Following on from this work, the approach has been successfully operationalised by forest managers across a substantial number of New Zealand's forests. Similar approaches are being researched, improved upon, and implemented in Australia's plantations (Rombouts et al., 2015), building on their rich history of ALS research (Rombouts et al., 2010; Stone et al., 2011).

Individual tree analysis (ITA)

Research into ITA is an exciting and rapidly changing area with considerable potential to provide detail on tree dimensions. The techniques generally rely on identifying and delineating the crowns of individual trees in the ALS point cloud and extracting tree-level metrics. These metrics can be used to measure tree traits directly, or to build empirical models that can be used to estimate variables of interest based on aspects of canopy size or shape.

Although somewhat challenged by GPS inaccuracies under a closed canopy and the requirement for denser point clouds, the implications of ITA for precision forestry are profound. As well as possibly opening the door for individual tree inventory practices, ITA also has the potential to provide a means of characterising the growth and performance of every tree in a subject forest. Through the production of metrics that can be used to characterise tree size, shape and form, ITA provides a means to more accurately characterise individual trees in stands and research trials, which could lead to an improved understanding of the factors influencing individual tree growth and wood quality. The wide-scale estimation of relevant tree characteristics could greatly enhance gains from genetically improved tree-stocks by enabling rapid identification and monitoring of trees with desirable qualities in the field.

Researchers at Scion are well placed to take full advantage of the opportunities presented by ITA, thanks to the significant gains made during the development of algorithms for tree counting from ALS point clouds within the Future Forest Research programme (Pont et al., 2015a; Pont et al., 2015b). The tree counting procedures provide a solid foundation for the subsequent delineation and characterisation of individual tree crowns for use in ITA research. In the coming years this research will form a fundamental component of the GCFF research programme, helping to 'phenotype' individual trees and ultimately tease out and quantify genetic and environmental effects on tree growth and quality.

Terrestrial laser scanning (TLS)

Most laser scanning applications that are developed for forestry use aerial platforms as this method of collection is well suited to the large scale of most forests. However for tree or plot-level measurements, or where very detailed measurements of tree characteristics are required, TLS may be a very useful tool. Traditional TLS systems are typically mounted on a tripod and provide hemispherical scans of their environment using a technology that is fundamentally the same as that employed in ALS. These devices are characterised by the ability to produce exceptionally detailed and accurate point clouds (Figure 2), and also the concurrent recording of photography, allowing the resulting point cloud to be coloured. This technology is widely used in the engineering industry to create 3D models of the built environment.

Figure 2: A tripod mounted (top) and mobile laser scanner (bottom) being used by Scion's researchers in New Zealand's forests with examples of the point clouds generated. Photos: Rod Brownlie

Mobile and hand-held laser scanners are more recent developments that offer considerable potential benefits for the forest industry. These devices are either mounted on a vehicle or carried by the operator and are capable of producing coherent point clouds from a moving platform (Figure 2). Compared to tripod mounted systems, mobile scanners typically have a smaller scanning range, lower accuracy and provide less detailed point clouds, but the ability to cover a large area quickly and to view objects from multiple locations is appealing for forest assessment. Scion have invested in a mobile laser scanner (ZEB1 unit developed by CSIRO) and have a comprehensive research programme underway to test the utility of both mobile and tripod mounted laser scanners for tree and forest measurements. Both TLS systems trialled have been capable of producing viable point clouds in a forest environment.

Numerous methods have been trialled for automated extraction of tree and forest structure from TLS data, and ongoing work is aimed at developing a tool specifically for scanning trees in New Zealand plantation conditions. This will be developed into a product capable of extracting useful tree and plot-level measurements in certain forest conditions, although a degree of understorey vegetation clearance is probably necessary. Further research is aimed at developing methods to estimate other less direct attributes from TLS point clouds including the LAI, disease expression, wood properties, biomass and fire loading.

Satellite imagery

Data from space-borne sensors on board orbital satellites have long been used to monitor climate, vegetation, land-use change, and to augment ground-based measurements. Since the 1972 launch of Landsat-1, the first civilian satellite tasked with observing the Earth, researchers have sought to develop methods to use satellite imagery to enhance our understanding of global systems and vegetation structure. These insights are supported by petabytes of repeat and detailed data from a range of Earth observing satellites, primarily provided by governmental organisations such as NASA and the European Space Agency (ESA). The great benefit of these platforms lies in the opportunity for a global perspective of the Earth's systems. The number of Earth observing satellites, and participating space agencies,

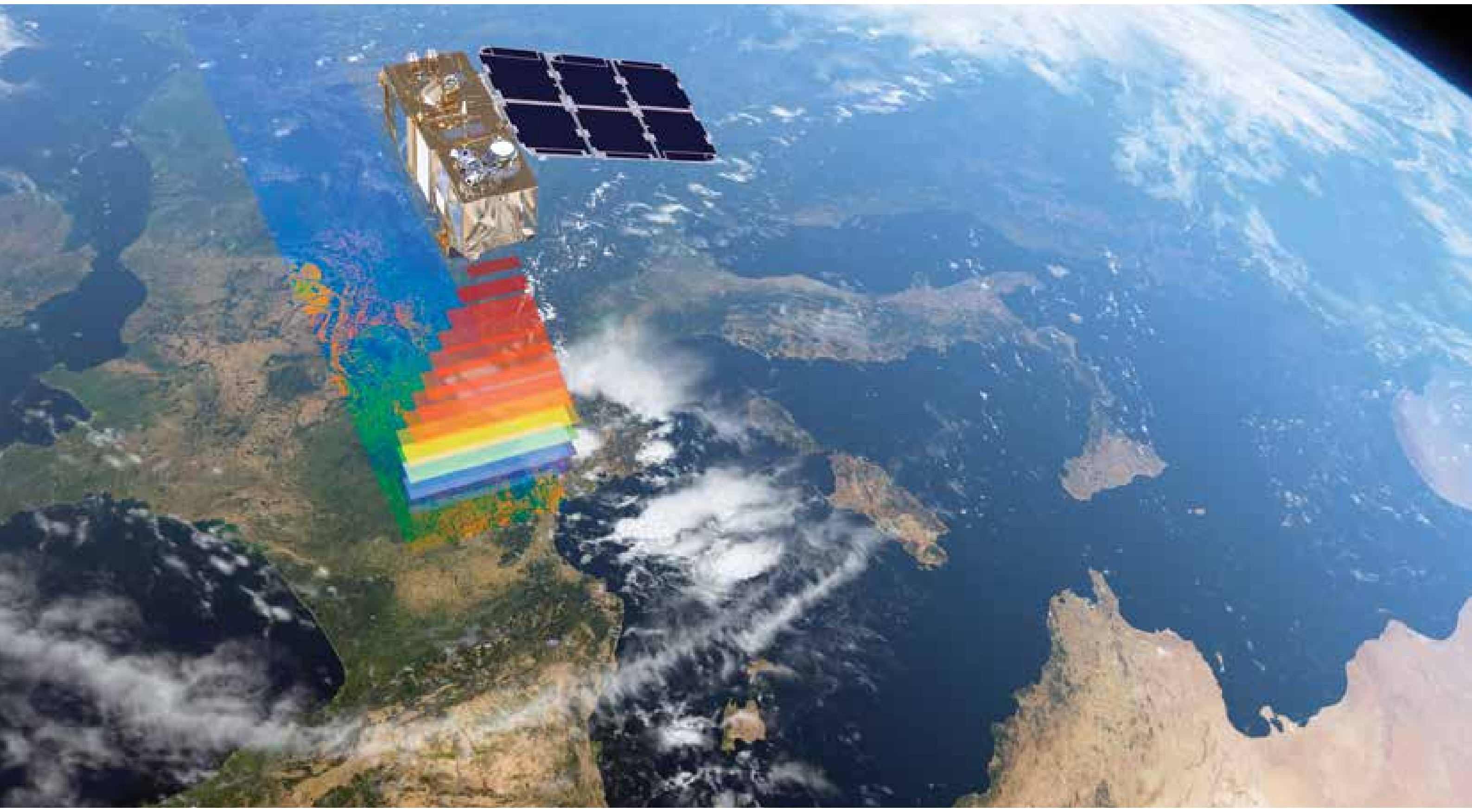

Figure 3: An artist's impression of the European Space Agency's Sentinel 2A satellite that provides 'colour vision' for ecosystem monitoring. Source: ESA

has increased dramatically over the past four decades, leading to a wealth of data with ever-increasing resolution, return frequency, more sophisticated sensors and rapidly decreasing data costs.

The recent proliferation of satellite data has fuelled a revolution in processing and analysis techniques, which take advantage of advanced visualisation techniques and distributed parallel processing facilities such as NASA's Earth Exchange and Google's Earth Engine. Working in combination, the latest generation of NASA's Landsat satellite (Landsat 8) and the ESA's Sentinel 2 (Figure 3), when fully operational, will image the entire global land area twice per week (Wulder and Coops, 2014). These developments, along with the free release of many image archives to researchers, have facilitated significant advances in research uptake and the understanding of global systems such as climate, carbon cycling and vegetation dynamics.

So how can satellite imagery be used by the plantation forest manager and what contribution can data from satellite imagery make to precision forestry? Data from satellite sensors has been used for forest resource assessment for at least a quarter of a century and forms a major component of national forest inventory and stand-wise inventory in many countries (Tomppo et al., 2010). A perennial issue with satellite data is that the imaging system is passive, relying on the sun to illuminate the scene, unlike active sensing technologies such as radar and LiDAR. Occlusions and variations in lighting due to clouds, fog and ambient light levels require complex calibrations and corrections to extract meaningful data. Early efforts to integrate satellite data in New Zealand (Tomppo et al., 1999) showed promise, but encountered problems, and were not adopted as part of routine inventory practice. A national inventory of carbon stocks (Stephens et al., 2012) uses land-cover classifications defined from satellite imagery, but does not use metrics extracted from the imagery in the prediction of forest parameters.

More recent research in New Zealand has focused on utilising data from higher resolution commercial satellites for forestry applications. Significant research effort has developed tools that use data from RapidEye, an array of five identical satellites that acquire imagery at a 5 m spatial resolution. RapidEye offers cost-effective pricing, regular return and 5-band multi-spectral imaging, including the 'red-edge' band that is sensitive to changes in chlorophyll content and that has been linked to plant health and productivity. Researchers at Scion have shown that RapidEye imagery can be useful for forest planning applications such as identifying harvested areas and areas of abnormal growth (Watt and Watt, 2011) and for accurately monitoring the extent of outbreaks of foliar disease. More recently, research undertaken as part of Scion's GCFF programme has used metrics extracted from RapidEye data in combination with other data sources

Table 1: Summary of planned satellite Earth observation fleets. Source: ESA, space.skyrocket.de, NASA, Bloomberg

Company	Fleet size	Product offering	Planned operation
PlanetLabs	150 + CubeSats	3–5 m multi-spectral	2015/2016
BlackSky Global	6 + medium satellites	1 m multi-spectral	2016
Google Skybox	24 + CubeSats	<1 m + live video	2016/2017
Axelspace	3 + CubeSats	2.5 m multi-spectral	2017
DigitalGlobe	5 + large satellites	Up to 30 cm super spectral	Now + 1 in 2016
UrtheCast	1 camera on-board ISS	24/7 high resolution live video from ISS	Now
HySpecIQ	2 medium satellites	Hyper-spectral	On hold

Note: data on funded or booked launches preferred, but not always available

\+ indicates publicly announced intentions to expand at a later date

(LiDAR and environmental surfaces) to predict the forest productivity indices Site Index and 300 Index (Watt et al., 2015; Watt et al., Submitted) and to estimate stand structural attributes (Dash et al., 2015b).

Despite the demonstrated uses for satellite imagery, results from a recent survey conducted by Morgenroth and Visser (2013) suggest that few forest management companies in New Zealand routinely use satellite data, with aerial imagery being much more common. High data costs were commonly cited by respondents as a barrier to uptake. This situation is likely to reflect the fact that many of the most promising applications for forestry lie in the use of high resolution imagery, which remains expensive to acquire. There are signs that this situation is changing, opening up new opportunities to integrate these data sources into management activities.

A major barrier to the provision and sale of high resolution imagery was removed in 2014, when the US Department of Commerce lifted restrictions on the sale of imagery with resolutions below 50 cm. However potential customers for these products have not yet seen new products or significant cost reductions. Indeed, the Earth observation sector has seen significant consolidation, with DigitalGlobe recently acquiring GeoEye Inc, including the GeoEye-2 (now WorldView-4) satellite scheduled for launch in 2016. DigitalGlobe now controls one of the largest fleets of sophisticated Earth observation satellites, and few competitors are capable of delivering similar product offerings in terms of spatial, spectral and temporal resolution.

Despite this consolidation, forest managers and researchers may still benefit from cheap and abundant satellite imagery in the medium term. The entrance of Silicon Valley entrepreneurs into the space launch sector has already reduced launch costs for future satellite platforms. In addition, several new ventures (many backed by Silicon Valley tech firms) have announced plans for several new fleets of Earth observation satellites (Table 1). Most of these new fleets eschew the traditional approach of launching a small number of very sophisticated satellites, with associated risk of failure, in favour of utilising smaller 'CubeSats'. Although these CubeSats cannot yet rival the spectral and spatial resolution of larger platforms, they are orders of magnitude cheaper and large fleets can provide near continuous observation of the entire Earth's surface. The reduced lifecycle will also allow future fleets to constantly integrate improvements in sensor performance. The merits of this approach were highlighted when PlantLabs Inc (the new owners of the RapidEye constellation) suffered the loss of dozens of CubeSats on two successive launch failures. Despite this setback, the company still maintains a large 'flock' of satellites, and plans to continue launch operations. Even if these trends in the space sector do not result in lower costs to forest managers, the advent of unmanned aerial systems capable of delivering rival products is likely to put further downward pressure on the price of remotely sensed imagery.

When used in combination with other forms of data sources, such as LiDAR and radar, satellite imagery has the potential to change the way forests are monitored and assessed. We foresee changes to management practices that increase efficiency, as information becomes more readily available to inform decision-making at reduced cost. This information may include just-in-time inventory, estimation of wood properties and biosecurity incursion monitoring in near real-time at large scales. We anticipate that this will all be delivered as web-based services that integrate publically available data with private company data.

Unmanned aerial vehicles (UAVs)

UAVs have received much media attention recently and the technology seems to have captured a place in the public's imagination. Traditional remote sensing made use of satellites and manned aircraft, but in recent years improvements in UAV technology, driven by longer flight times and greater carrying capacity, have made them a viable platform for data capture. Sensor hardware manufacturers have recognised this, with several of the major players producing UAV-specific

Figure 4: A multi-rotor UAV similar to the device developed for Scion by Aeronavics Ltd that will provide a platform for research into precision forestry and samples of 5-band multi-spectral imagery and ALS data acquired with the device. The multi-spectral image shows wilding pines visible in purple, the ALS image shows a dense point cloud collected over a mature radiata plantation in the Bay of Plenty. Photo: Aeronavics Ltd, Scion

sensor hardware and numerous start-up companies founded to deliver new options for remote sensing from UAV. The current Civil Aviation Authority (CAA) regulations limit the use of UAVs in New Zealand to flight within the operator's line of sight and during daylight hours only, which limits certain immediate applications in the forestry sector.

Whilst the operational restrictions remain strict, and rightly so, professional UAV operators can apply for accreditation under part two of the CAA rules, resulting in a relaxation of restrictions in certain circumstances. The combined pressure from technological advances, significant potential benefits and the weight of public expectation seem likely to result in the removal of the legislative barriers sooner or later. It is not yet clear whether a technological or legislative development will open the door for the extended use of UAVs, but it is inevitable that they will play an increasingly important role in precision forestry. The key advantage of UAVs compared with traditional platforms is one of cost. Low cost and flexible data acquisition means that the spatial resolution of data collected will be reduced and the frequency with which we can afford to collect data will be greatly increased.

Although UAV technology is still in its infancy numerous research teams have published scientific literature on the development of navigation systems, communications, mission deployment software and sensor integration. Readers are directed to Pajares (2015) for a comprehensive review of the current state of UAV research. The deployment of UAVs for agricultural purposes is relatively well advanced, and devices have been used successfully for the detection of weed infestations (Peña et al., 2013), crop condition and yield monitoring (Agüera et al., 2011). This information has then been used to improve the application of fertilisers, irrigation and weed control measures to increase productivity and maximise the efficiency of inputs. Application of this technology to small-scale horticultural crops, such as citrus orchards, olive groves and vineyards, are also commonly reported in the literature. Developments in the forestry sector have been somewhat slower, and are hampered by the larger crop areas and more difficult terrain related to the inherently lower value of plantation tree crops compared to agricultural products.

A team from the University of Tasmania has made significant progress in developing UAVs for forest measurement. Wallace et al. (2012) mounted a laser scanner and visible video camera on board an octo-copter UAV, with a limited flying range (200 m), and used this to collect very dense point clouds (65 points per m^2). These point clouds were used to extract tree heights, locations and crown widths. The same device was also used for monitoring growth and measuring the pruned height of a young *Eucalyptus globulus* stand (Wallace et al., 2014). Further research by the same group provided a detailed assessment of the utility of data from the system they developed for several applications of interest to forest managers including change detection, canopy mapping and tree detection. Other UAV applications with relevance to forestry include monitoring forest health, soil monitoring, environmental monitoring, biodiversity analysis and land-use classification.

Photogrammetry has a bright future when combined with UAV platforms, as the advent of miniaturised inertial measurement units and readily available computing power facilitates the production of photogrammetric products at high resolution and low cost for small areas. Suitably equipped UAVs can collect sufficient imagery to reconstruct 3D structure from overlapping 2D photographs, and these have been widely used to produce digital terrain models and digital surface models, which are useful for many applications. From a forestry perspective, the application of photogrammetric techniques to produce high density point clouds of forests is a field with an extraordinary potential to provide a cost-effective means for forest assessment that could rival the benefits of ALS at a much reduced cost. One limitation

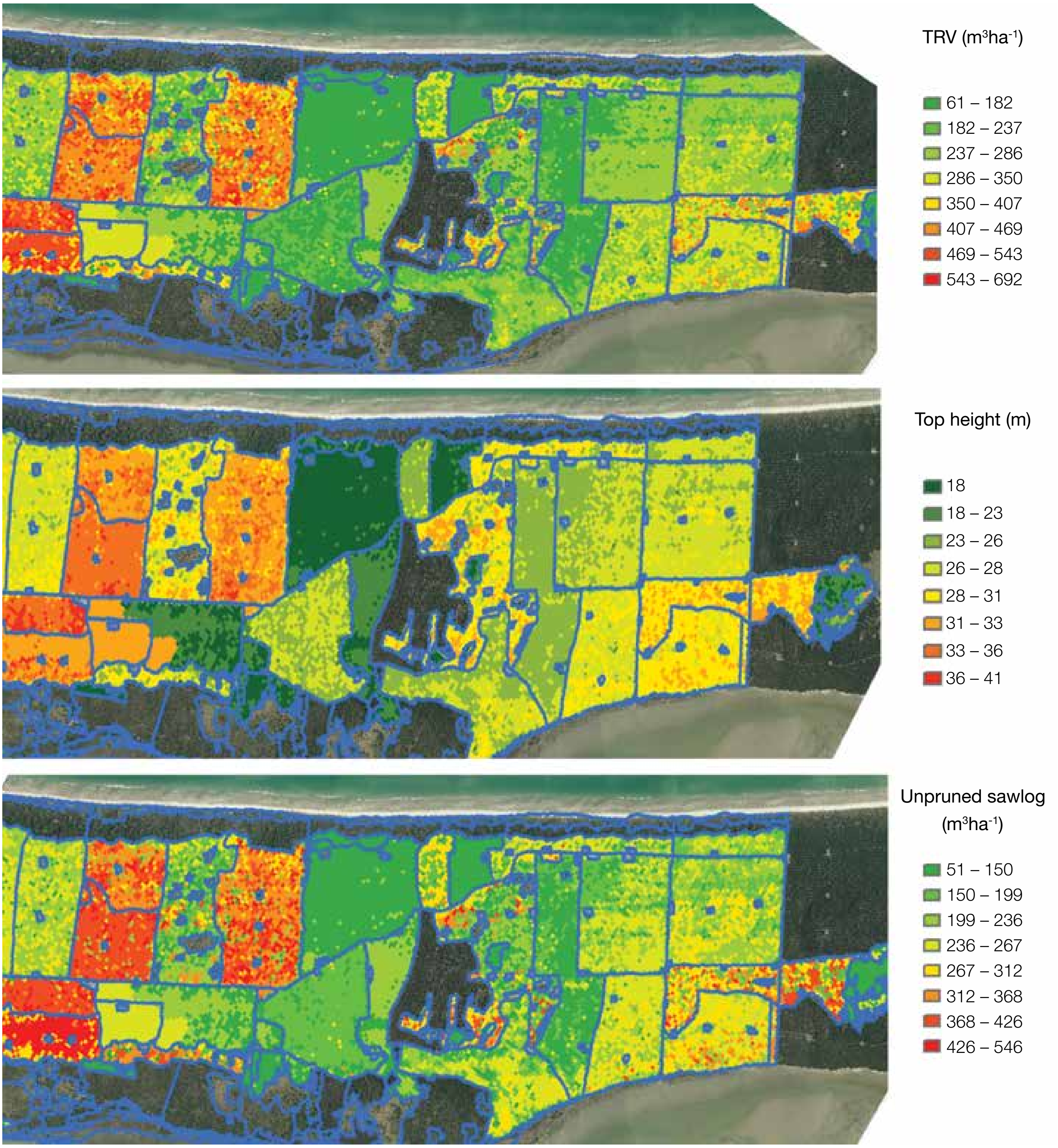

Figure 5: Maps of total recoverable volume (TRV), top height and unpruned sawlog volume estimated using k-NN and ALS data for a New Zealand *Pinus radiata* plantation

of this methodology for forest assessment is an inability to detect the terrain when imaging tree covered areas. However this limitation can be circumvented if there is a pre-existing DTM for the area of interest, which allows the point cloud to be normalised with respect to the ground.

Because the potential applications for UAVs in forestry are extensive, there are a number of entrepreneurial companies that are developing and offering UAV services to the forestry sector. Applications that hold considerable potential include cutover mapping, survival assessment, acquisition of photogrammetric point clouds, targeted LiDAR acquisition for specific areas of interest or discontinuous forest resources, post-harvest waste assessment, and loss assessment following catastrophic weather events. In recognition of this potential, Scion has invested in a state of the art multi-rotor UAV platform. The Scion UAV (Sci-Fly) was developed in partnership with local start-up Aeronavics who have honed their skills providing aerial platforms for the movie industry. Scion's UAV platform is equipped with a laser scanner, capable of quickly collecting dense point clouds, and various cameras suitable for forestry-specific imagery capture. You can expect to see the device deployed on research missions throughout New Zealand from mid-2015 onwards. Scion's remote sensing team has positioned itself to address the gap between the conceptual and realised application of these tools through the development and evaluation of technologies and supporting science. Through working with selected industry partners, Scion's UAV research programme aims to develop robust and practical tools that will help deliver the benefits of precision forestry to the sector.

Spatial surfaces of forest attributes

An important output of remote sensing is the ability to spatially map forest characteristics over areas of interest. Examples of these areas may be stands, harvest coups, riparian areas, whole forests or even entire landscapes. Spatial maps, detailing the distribution of forest attributes through the resource (Figure 5), are a key enabler of precision forestry. High resolution spatial maps describing variation in height are useful for accurately scheduling thinning and pruning operations that depend on the crop reaching a threshold height. Maps describing spatial variation in stand attributes and log-grade output provide more detailed forest resource descriptions; this will potentially facilitate more accurate planning of harvest operations and improved segregation. Development of productivity indices from LiDAR, such as the Site Index and 300 Index, provide a useful means of spatially stratifying the resource in a way that cannot be achieved with conventional stand-level information. The new knowledge afforded by these maps should deliver a challenge to forest managers: how can this information best be used to deliver more efficient, better informed, forest management that facilitates increases in profitability and sustainability?

Conclusion

The future for remote sensing research at Scion is rich with possibilities and new challenges. Future developments will further our understanding of forest growth and generate novel tools and opportunities that advance precision forestry and increase productivity and profitability. Current research is focused on modelling the phenotypic characteristics of plantation grown trees to further research into the development and deployment of improved genetic material, developing methods to better understand wind damage risk, modelling LAI for New Zealand's plantations, and using precise models of forest productivity generated from ALS to guide forest management practice.

Rapid technological developments are continuously redefining the role of remote sensing in forest management and as a result precision forestry is fast becoming an attainable reality. The sensor revolution will continue to deliver a growing volume and variety of data describing the attributes of our plantations at an ever-increasing resolution. Researchers face the challenge of developing tools and techniques that can be used to extract useful information from this data in a usable and timely manner. Forest managers face the challenge of adjusting their business practices so that they can position themselves to take advantage of the tools of precision forestry.

Acknowledgements

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References

Adams, T., Brack, C., Farrier, T., Pont, D. and Brownlie, R. 2011. So You Want to Use LiDAR? – A Guide on How to Use LiDAR in Forestry. *New Zealand Journal of Forestry*, 55:19–23.

Adams, T. and Pont, D. 2012. Projecting Plots in LiDAR – Correcting for Slope in Remotely Sensed Data. *New Zealand Journal of Forestry*, 57: 25–31.

Agüera, F., Carvajal, F. and Pérez, M. 2011. Measuring Sunflower Nitrogen Status from an Unmanned Aerial Vehicle-Based System and an On The Ground Device. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives*, pp. 33–37.

Chen, Y., Tapper, N., Zhu, X., Kilinc, M. and Harris, S. 2014. Use of LiDAR Technology in Forest Fuel Structure Measurements for Development of Dynamic Fuel Hazard Models. In *Proceedings of SPIE – The International Society for Optical Engineering*.

Dash, J.P., Marshall, H.M. and Rawley, B. 2015a. Methods for Estimating Multivariate Stand Yields and Errors Using K-NN and Aerial Laser Scanning. *Forestry*, 88: 237–247.

Dash, J.P., Watt, M., Bhandari, S. and Watt, P. 2015b. Characterising Forest Structure Using Combinations of Airborne Laser Scanning, Rapideye Satellite Imagery and Environmental Variables. *Forestry*, 88.

Gobakken, T., Næsset, E., Nelson, R., Bollandsås, O.M., Gregoire, T.G., Ståhl, G., Holm, S., Ørka, H.O. and Astrup, R. 2012. Estimating Biomass In Hedmark County, Norway Using National Forest Inventory Field Plots and Airborne Laser Scanning. *Remote Sens. Environ.*, 123: 443–456.

Hill, R.A. and Broughton, R.K. 2009. Mapping the Understorey of Deciduous Woodland from Leaf-On and Leaf-Off Airborne Lidar Data: A Case Study in Lowland Britain. *ISPRS Journal of Photogrammetry and Remote Sensing*, 64: 223–233.

Maclean, G.A. and Krabill, W.B. 1986. Gross-Merchantable Timber Volume Estimation Using an Airborne Lidar System. *Canadian Journal of Remote Sensing*, 12: 7–18.

McRoberts, R.E., Cohen, W.B., Erik, N., Stehman, S.V. and Tomppo, E.O. 2010. Using Remotely Sensed Data to Construct and Assess Forest Attribute Maps and Related Spatial Products. *Scand. J. For. Res.*, 25: 340–367.

Morgenroth, J. and Visser, R. 2013. Uptake and Barriers to the Use of Geospatial Technologies in Forest Management. *New Zealand Journal of Forestry Science*, 43: 1–9.

Naesset, E. 2007. Airborne Laser Scanning as a Method in Operational Forest Inventory: Status of Accuracy Assessments Accomplished In Scandinavia. *Scand. J. For. Res.*, 22: 433–442.

Pajares, G. 2015. Overview and Current Status of Remote Sensing Applications Based on Unmanned Aerial Vehicles (UAVs). *Photogramm. Eng. Remote Sensing*, 81: 281–329.

Peña, J.M., Torres-Sánchez, J., de Castro, A.I., Kelly, M. and López-Granados, F. 2013. Weed Mapping in Early-Season Maize Fields Using Object-Based Analysis of Unmanned Aerial Vehicle (UAV) Images. *PLoS ONE*, 8.

Pont, D., Kimberley, M., Brownlie, R.K., Morgenroth, J. and Watt, M.S. 2015a. Tree Counts from Airborne LiDAR. *New Zealand Journal of Forestry*, 60: 38–43.

Pont, D., Kimberley, M.O., Brownlie, R.K., Sabatia, C.O. and Watt, M.S. 2015b. Calibrated Tree Counting on Remotely Sensed Images of Planted Forests. *Int. J. Remote Sens.*, 36: 3819-3836.

Rombouts, J., Ferguson, I.S. and Leech, J.W. 2010. Campaign and Site Effects in LiDAR Prediction Models for Site-Quality Assessment of Radiata Pine Plantations in South Australia. *Int. J. Remote Sens.*, 31: 1155–1173.

Rombouts, J., Melville, G., Kathuria, A., Rawley, B. and Stone, C. 2015. Operational Deployment of LiDAR Derived Information into Softwood Resource Systems. *In Forest and Wood Products*, Australia.

Stephens, P.R., Kimberley, M.O., Beets, P.N., Paul, T.S.H., Searles, N., Bell, A., Brack, C. and Broadley, J. 2012. Airborne Scanning LiDAR in a Double Sampling Forest Carbon Inventory. *Remote Sens. Environ.*, 117: 348–357.

Stone, C., Penman, T. and Turner, R. 2011. Determining an Optimal Model for Processing Lidar Data at the Plot Level: Results for a *Pinus Radiata* Plantation in New South Wales, Australia. *New Zealand Journal of Forestry Science*, 41: 191–205.

Tang, H., Brolly, M., Zhao, F., Strahler, A.H., Schaaf, C.L., Ganguly, S., Zhang, G. and Dubayah, R. 2014. Deriving and Validating Leaf Area Index (LAI) at Multiple Spatial Scales Through Lidar Remote Sensing: A Case Study in Sierra National Forest, CA. *Remote Sens. Environ.*, 143: 131–141.

Tomppo, E., Goulding, C. and Katila, M. 1999. Adapting Finnish Multi-Source Forest Inventory Techniques to the New Zealand Preharvest Inventory. *Scand. J. For. Res.*, 14: 182–192.

Tomppo, E., Gschwantner, T., Lawrence, M. and McRoberts, R. 2010. *National Forest Inventories: Pathways for Common Reporting*. Springer: Heidelberg, Dordrecht, London, New York.

Wallace, L., Lucieer, A., Watson, C. and Turner, D. 2012. Development of a UAV-LiDAR System With Application to Forest Inventory. *Remote Sensing*, 4: 1519–1543.

Wallace, L., Watson, C. and Lucieer, A. 2014. Detecting Pruning of Individual Stems Using Airborne Laser Scanning Data Captured from an Unmanned Aerial Vehicle. *International Journal of Applied Earth Observation and Geoinformation*, 30: 76–85.

Watt, M., Dash, J.P., Bhandari, S. and Watt, P. Submitted. Multi-Sensor Modelling of Forest Productivity Using Combinations of Airborne Laser Scanning, High Resolution Rapideye Satellite Imagery and Environmental Data. *Canadian Journal of Forest Research*.

Watt, M.S., Adams, T., Aracil, S.G., Marshall, H. and Watt, P. 2013a. The Influence of LiDAR Pulse Density and Plot Size on the Accuracy of New Zealand Plantation Stand Volume Equations. *New Zealand Journal of Forestry Science*, 43: 145–154.

Watt, M.S., Adams, T., Watt, P. and Marshall, H. 2013b. Influence of Stand and Site Conditions on the Quality of Digital Elevation Models Underlying New Zealand Forests. *New Zealand Journal of Forestry Science*, 43: 39–47.

Watt, M.S., Dash, J.P., Bhandari, S. and Watt, P. 2015. Comparing Parametric and Non-Parametric Methods of Predicting Site Index for Radiata Pine Using Combinations of Data Derived from Environmental Surfaces, Satellite Imagery and Airborne Laser Scanning. *For. Ecol. Manage.*, 357: 1–9.

Watt, M.S., Meredith, A., Watt, P. and Gunn, A. 2013c. Use of LiDAR to Estimate Stand Characteristics for Thinning Operations in Young Douglas-Fir Plantations. *New Zealand Journal of Forestry Science*, 43: 175–184.

Watt, M.S., Meredith, A., Watt, P. and Gunn, A. 2014. The Influence of LiDAR Pulse Density on the Precision of Inventory Metrics in Young Unthinned Douglas-Fir Stands During Initial and Subsequent Lidar Acquisitions. *New Zealand Journal of Forestry Science*, 44: 1–9.

Watt, P. and Watt, M. 2011. Applying Satellite Imagery for Forest Planning. *New Zealand Journal of Forestry*, 56: 23–35.

Watt, P. and Watt, M.S. 2013. Development of National Model of *Pinus radiata* Stand Volume from Lidar Metrics for New Zealand. *Int. J. Remote Sens.*, 34: 5892–5904.

Wulder, M.A. and Coops, N.C. 2014. Satellites: Make Earth Observations Open Access. *Nature*, 513: 30–31.

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