In this issue

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Volume 66, Number 4
February 2022

Front cover photo: Puhinui Reserve project (March 2020).

Back cover photo: Young girl plants native seedling as a living memorial at a Matariki Tu Rākau planting day in Te Ruapekapeka, Northland. See: www.mpi.govt.nz/forestry/funding-tree-planting-research/matariki-tu-rakau/

Photos courtesy of Te Uru Rākau – New Zealand Forest Service

Guest editorial

Tim Payn

Nothing lasts forever – so says Sebastian Klinger in this issue's *Last word*. This is particularly relevant in today's fast-changing world, I don't think there has been such a rate of change in so many things in human history as today – this has been termed the 'Great Acceleration', and the epoch the Anthropocene, reflecting human's impact on the planet. This issue of the journal takes a future-focused look at some aspects of forestry in Aotearoa New Zealand.

I've always personally had an eye on the future. Dreaming of what might be: anti-gravity logging machinery, terraforming and afforesting Mars, or breeding square trees for ease of processing. What can we dream of for our forests? Creative and visionary people built New Zealand forestry – we stand on the shoulders of giants. Who are our giants of today, or more importantly the giants of tomorrow, who will take our forests to the next century? What will they need to get us there?

We have come far: from the Royal Commission in 1913, recognising we could not continue to depend on our indigenous forests; through the radiata pine task force that developed the first intensive plantation forestry management systems; to, more recently, transformational harvesting technologies for the 65% of our plantation harvest that comes off steeplands. We are also at the cutting edge of forest conservation with a global reputation based on refugia (pest-free islands), whether on or offshore. This creativity and thinking has had a massive national and global impact.

So, what's important for the future of our forests? People and passion first and foremost. In the last few years, we have seen the emergence of a whole raft of initiatives aimed at younger people and informing and educating them about forests, forestry and careers. Alfred Duval of Future Foresters outlines their vision in this issue, the NZIF Foundation encourages students through awards (please donate today) and other groups (such as the WIDE Trust, Te Uru Rākau – New Zealand Forest Service) and the regional Wood Councils are very active in school programmes, scholarships and internships. Young people are the future, and we need to excite them about forests, which after all make up around 31% of both our terrestrial landmass and the planet's land cover.

Understanding forests is second – they are living breathing entities and far more complex than most people know – read Peter Wohlleben's great book *The Hidden Life of Trees*. Trees talk to each other! We do tend to have a simplistic view of forests – 'Oh it's just an exotic plantation.' That plantation depends on a complex ecology just as tropical rainforests do – microbes, fungi, bacteria, insects, plants, animals, birds, trees all interacting. Let's teach our kids (and their parents) about ecology and how all living and non-living things fit together in a forest.

Then technology – the AI revolution and the Internet of Things – have turned forestry on its head. It's so easy now to do things on a smart phone, with no need to visit the forest. Dial up a satellite, download tree locations to your phone and off you go to do some wilding control, as we have been doing on a friend's block of regenerating forest recently. Technology opportunities are huge, and Claire Stewart and Robin Hartley give us a perspective on some of these.

Biotechnology and genomics to rapidly accelerate breeding programmes are covered by Mark Paget, another game-changer, as are the new nursery technologies outlined by Sebastian Klinger. Looping back to education and training though, one of the most exciting technology advances I've seen recently is the use of virtual reality for training. Toi Ohomai Institute of Technology has pioneered training for forest machine operations on video-based simulators, dramatically shortening training time – and also very attractive to a generation of young people raised on video gaming. This recognises the importance of mechanisation and health and safety in the forest. Toi Ohomai is about to double their capacity with the commissioning of a container-based mobile facility to reach students in remote areas. It's not a great leap to remotely operated machinery, allowing people to live far from the forest.

Other papers in this issue reflect the future and recent advances moving us ahead. Jason Wilson outlines the vision of a transformed forestry sector in a rapidly changing world and Te Uru Rākau – New Zealand Forest Service's role in this transformation. Glen Murphy looks at opportunities from automated log tagging to improved production efficiencies as part of the push to develop innovative harvesting technologies in forestry automation and robotics. Volga Lipwoni and colleagues at Scion and the University of Canterbury put forward new ways of estimating tree heights from 3D LiDAR point clouds he developed in his Masters programme, an exciting part of the revolution in forest inventory.

I will finish by reflecting again on our giants of forestry. Professor Geoff Sweet's obituary is in this issue. He was Prof at Canterbury when I was there – a gentleman and a scholar who had an eye on the future and those who would steward it.

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Future Foresters – history and into the future

Alfred Duval

Abstract

Future Foresters is a Special Interest Group under the New Zealand Institute of Forestry. This paper outlines the history of how FF developed, its five key objectives, its current structure and funding (especially FRESTRA Club funding), and the future of FF.

Development of the FF Special Interest Group

You may have seen one of our t-shirts, watched one of the careers videos on social media, attended a quiz night, or know a young forester who has benefited from training and networking. Hopefully, by now, the New Zealand forest industry as a whole has heard of the Future Foresters (FF).

It all began at the 2017 NZIF conference and the question: 'Why doesn't forestry have its own form of Young Farmers?' We sat around that table, knew many of our peers throughout the country, and were left wondering why we didn't have a chance to network as we entered into the industry.

As foresters in the making, we were becoming acutely aware of forestry's issues, but increasingly unaware of any successful efforts trying to work towards resolving them. Forestry's issues are nothing new: poor public perception, lack of positive stories, lack of engagement from the younger generation, lack of enrolment in forestry courses, an ageing workforce etc. We naively thought we might be able to do something about it. We knew the issues, and thought that if we could create a forestry community for young or new entrant foresters in New Zealand it would at least be part of the solution to some of these problems.

With minimal experience and a pinch of drive our aim was to help build a stronger, more connected and more diverse forest industry by linking foresters throughout the country. From the beginning we said: 'If we fail, then we will learn. If we succeed, then we have helped to make a stronger and more united industry.'

Just over three years ago, there wasn't a connected community of young foresters in New Zealand. There wasn't a collective presence of young foresters on social media, there were no young forester events, there was no representation on industry bodies. There was no ability to connect across forest, regional and company boundaries to allow the next generation of foresters to feel welcomed, supported and a part of the industry. This meant there was no network of passionate young foresters who got together and shared a love for trees, their products and the people in the industry.

Figure 1: Future Foresters at Feilding Field Days

It has been an incredible journey to see the idea transition from seed to sapling, but more so in witnessing the FF community coming together from nothing. To now have the opportunity for young foresters to connect with recent graduates and those new to the regions, that is what FF is all about.

Five key objectives

Being a Special Interest Group under the NZIF holds FF to account under the Institute's Code of Ethics. It also means that we have a seat on, and report quarterly to, the NZIF Council. NZIF support has allowed us to focus on what we do best without being swamped by the administration load of running our own individual organisation.

FF has five main objectives:

1. Create a diverse community of foresters in New Zealand through social and professional networking opportunities.

2. Provide professional development opportunities for early career foresters.

3. Provide a relatable face for forest industry career promotions to the next generation of foresters.

4. Provide a voice for young foresters involved in all aspects of forestry in New Zealand.

5. Connect new foresters with those more experienced.

Although there are five objectives, the foundational goal of FF is to create a sense of community. It is our firm belief that without achieving and focusing on fostering community for young foresters our ability to achieve the other objectives would be severely limited.

FF's success thus far can be measured across the five key objectives:

Objective 1

Through networking events (in person and online), branding (FF logo and over 150 t-shirts), and our presence at conferences, workshops and industry events, a sense of forestry community has been created throughout New Zealand and we strive to grow this to a stronger presence in the forestry workforce. Through Facebook we have 250 members and through our mailing list we have over 350.

Objective 2

Mental Health First Aid, public speaking and negotiation training have been run throughout the country, as well as regional workshops, such as the recent Interpine/Hovermap workshop in Rotorua.

Objective 3

FF successfully ran three social media campaigns, with 10 young forester videos seen by many people outside of the industry who would not normally have been exposed to forestry (video views have now reached 645,125). The recent campaign beginning in August 2021 has driven over 8,000 clicks through to the www.forestrycareers.nz website and reached over 100,000 unique people.

Objective 4

FF representatives sit on a wide range of industry groups and committees: the NZ Forest Owners Association (FOA) Training and Careers Committee, the FOA Biosecurity Committee, the NZIF Council and the Forestry and the Wood Processing Workforce Action Council.

Objective 5

Through industry involvement FF has connected more with the older generation in the industry. Admittedly, there is still work to be done but all ages in the industry are welcome to FF events.

Structure

FF has an Executive Committee of four people who run the nationwide initiatives and campaigns, source and apply for funding, report to the NZIF Council and funding providers, engage with industry partners, and coordinate the Regional Leaders and annual planning session.

There are currently seven Regional Leaders throughout New Zealand who deliver local training, networking and careers events, assist with FF events during the year, and who aim to connect together all young foresters in their region. The Regional Leaders were launched in 2020 after it became apparent how difficult it was for just the Executive Committee to connect at a local level with all the young foresters in each region without being based there.

The leadership meets every year (around October) to plan the following year's events, the annual theme and social media campaigns. Planning for 2022 was held in October 2021 in Christchurch, which coincided with an excellent opportunity sponsored by Te Uru Rākau to take fourth year forestry students out to dinner and interact with the latest cohort of soon-to-be forestry graduates.

Funding

Core funding for FF comes from an annual application to the FOA Training and Careers Committee, which delivers funding via the Forest Growers Levy Trust (FGLT). This was the first-ever funding FF was able to access and has been consistent since it started. It provides the resources needed for professional development events (e.g. public speaking training or Mental Health First Aid courses) and for attending careers events with instantly recognisable FF t-shirts.

For industry promotion FF coordinates social media campaigns, which have been exclusively supported by the Wood Industry Development and Education Trust (WIDE). The Trust have been extremely supportive and critical to our success by assisting with resourcing for video creation, social media campaigns and associated advertising costs that have become a core part of FF's public outreach.

In 2021, Te Uru Rākau provided one-off funding for special projects, which allowed FF to continue with some of its 2021 plans when other funding fell short.

HOW?

Establish
a *community* of young foresters.

A place where foresters can engage with the industry and feel part of the collective group.

Increase
the number of young people who *choose* forestry as an industry.

Build
engagement and *awareness* of forestry as a diverse and rewarding profession within schools and tertiary providers.

Figure 2: Future Foresters NZ high-level strategy – 'Establish, Increase, Build'

The FRESTRA Club

A serendipitous message out of the blue in August 2018, coincidentally at the first-ever FF planning session, began what has been a three-year journey involving FF and FRESTRA. The relationship and realisation of synergies between the two entities has culminated in FF becoming guardians of a significant amount of funding that has roots that trace all the way back through the club to the original New Zealand Forest Service.

The FRESTRA Club, formed in 1982, was a social club located on campus at the Forest Research Institute with the purpose of providing social connection for the Rotorua forestry community. The name FRESTRA came from the telegraphic address of the Forestry Research Institute in Rotorua and training centre. When in operation it would provide revenue to the club to take care of a property in Papamoa for use by club members. This property was affectionately known as the FRESTRA bach and was gifted to the club by the outgoing Forest Service as it was being discontinued in the late 1980s.

After 38 years of operating and providing a social environment for foresters to connect and share stories, the difficult decision was made to sell the FRESTRA bach and look for a way to wind the club up. Fast forward to November 2021 and FF is now the humble custodian of what is a historically significant set of funds. With the gifting of this fund, FRESTRA has solidified FF as a key stakeholder in the New Zealand forest industry in perpetuity.

FF is immensely grateful to the past and recent members of the FRESTRA Cub and the Forest Service for passing on the torch all those years ago. The fund will be aptly named the 'FRESTRA Fund' and will sit with NZIF, but only to be used for FF activities. The aim of the fund is to create a non-declining and self-sustaining revenue stream that will enable FF to continually support and connect young foresters within New Zealand, with an annual budget to further the five key objectives.

The FRESTRA funding opportunity forced FF to formalise its structure under the NZIF and to clarify key issues of succession and responsibilities. The four of us who founded FF are slowly becoming foresters. Although we still all have an immense passion and much to add to the industry, it is time we began the process of passing on the torch and allowing other young foresters the opportunities we have been exposed to through being involved in FF.

Beginning in 2022, there will be an annual application process for those in the industry who wish to be a part of organising and running FF to apply for either Executive Committee or Regional Leader positions. This will be run in conjunction with the annual process for the NZIF Foundation Awards. Executive Committee members will be selected by the current committee and the NZIF Council and the Regional Leaders will be decided by the Executive Committee. NZIF and FF have the opportunity to encourage the next cohort

Figure 3: Future Foresters brand logo

of enthusiastic foresters to continue the growth and impact of FF for the betterment of the entire industry.

The future of FF

The future of FF is in the hands of our young foresters and the industry at large. The progress made so far has come from our personal motivation and enthusiasm combined with unfaltering support from peers and employers. Without the support of time, finance and encouragement we wouldn't have got to this point, so I urge all forest industry employers and managers to encourage young foresters to be involved in whatever small way with FF. The benefits to their careers, their knowledge base and their network connections are invaluable, and the benefits to the industry are already being felt.

An ideal future for FF would be a connected forest industry across all those who interact with forests for both work and play. FF could be the conduit to connect contractors, conservationists, technology providers, sawmillers, researchers, entrepreneurs and foresters with all those involved in trees, wood, land and the environment.

The ideal future will also see FF continuing to be recognised as a key voice at the table of industry groups and given opportunities to prove their value and provide insight into the thinking of the next generation. FF will continue to connect, share, tell stories, develop, grow, and have fun as part of a diverse and rewarding community of people who care about trees and the power of wood as the ultimate renewable.

FF will continue to work with the soon-to-be established Global Network for Forestry Young Professionals (ForYP) to help link young Kiwi foresters to those around the globe. This will strengthen not only the New Zealand forest industry, but all foresters around the world through connections previously not possible.

100 years from now

For those interested in what New Zealand forestry might look like in 2121, there has been a thought-provoking article written recently by young foresters Sheridan Ashford (Commercial Sales Manager at Summit Forests New Zealand) and Adrian Loo (ETS/Project Manager at Forest Management Ltd). The article 'Haere taka mua, taka muri. Kaua e whai' was first published in March 2021 in *O Tātou Ngāhere* (Our Forest) by Pure Advantage and Tāne's Tree Trust. An excerpt can be found in the side box.

Conclusion

The enthusiasm and passion for forestry, and the recognition of the power of networking and the support (from industry, peers, funding providers and FRESTRA), has allowed FF to flourish to become a part of the New Zealand forest industry. It is important for all involved in forestry for FF to be here in the long run, as a core part of connecting foresters throughout the country, and a pivotal part of a young forester's journey on a diverse and rewarding career path that appreciates their input and supports them as a valuable part of the sector.

Acknowledgements

FF is grateful for ongoing support from not only the NZIF, the WIDE Trust and the FRESTRA Club, but FGLT, the FOA, Te Uru Rākau, Port Blakely, Summit Forests, Forest Management Ltd, Rayonier/Matariki and a number of individuals who are too numerous to mention.

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'Haere taka mua, taka muri. Kaua e whai. Go in front, not behind. Don't follow!' – Māori proverb. Sheridan Ashford and Adrian Loo

'Now in 2121, New Zealand is a tree-loving heaven. We are not only ranked #1 for Rugby, Sailing and Olympic surfing, but we are also ranked #1 globally for personal wellbeing for over 60 years running. This ranking is 100% purely related to the trees we have and the forests we support to grow in our country. New Zealand, once again, is now regarded as the most beautiful place on earth; we have long been pest-free and people pay a fee to log in virtually to experience the grandeur of our birdsong chorus.

'The world has united in the use of cryptocurrencies; no foreign exchange risk and no uncertainty in the value of a dollar. This change brought about a globally recognised and valued green cryptocurrency, invented in New Zealand called the 'Kākāriki'. This green dollar rewards all Land Guardians that ensure more and more environmental protection is occurring.

'The land is more valuable than anything and the people with trees are considered "green billionaires". People realised they didn't want to live in cities and didn't need to spend their life's earnings on a small cube in downtown Seymore-Ville (formerly Remuera). The Kiwi-dream is now to ditch the traffic jam and migrate from the cities to become a Land Guardian. People realise that the land that surrounds us can provide food, fodder and an opportunity to offset the residual carbon emissions from their grandparents.

'Everything is now made from wood. These woody products are sourced from our "New Zealand Forests"; a never-ending system of continuous cover forestry that provides woody biomass for us and our future generations. Housing continues to transform from the grey steel and concrete jungle of the past with the rich, golden syrup tones of Totara, Matai and Rimu abodes peppering the landscape. New Zealand has been smoke-free for over 80 years, plastic is illegal, fossil fuels are gone, electric self-driving vehicles rule our roads and zero-emission boilers fuel our biocircular economy. Our tourism thrives as electric planes deliver tourists; arrival taxes reflect New Zealand's values and each tourist must plant a tree, protect a waterway or undertake an action that results in a cleaner greener New Zealand.

'In 2121 sustainability is a salary and the Land Guardians are rewarded for the positive externalities they provide. For years forests were considered nothing more than an offsetting source for emitters and polluters, however, now through widespread societal recognition, the industry of sustainability no longer "offsets" but exists to "undo" the damage of our past generations. The industry of sustainability is a leader in new job creation enabling diverse economic opportunities.

'Land use no longer prioritises profits in the historical sense. Returns are now realised through environmental improvements, cleaner air, even cleaner water, and a landscape that all Kiwis admire. Many of those original tree-huggers or eco-warriors are now among the rich-listers. People invest for dividends of improved wellbeing as opposed to the singular financial driver of the olden days and returns on all investments are reported in both financial and wellbeing terms. This wealth is being redistributed straight back into New Zealand's environmental ecosystem; investment in the environment is internationally recognized as the best option for ethical wealth creation for others.

'Whakatupu is taught in all schools. Before maths or chemistry, we must learn to look after the land, so she looks after us. All children are taught about the importance of soil conservation and water quality, creating a passion for the environment in these young, green leaders.

'Through the last century, millions of these green leaders held New Zealand responsible to ensure we will always be a green nation. The force of our green revolution, driven by the millions of Kai Tiaki looking after their beautiful country.'

A digital future for New Zealand forestry

Claire Stewart and Robin J.L. Hartley

Figure 1: Photo depicting future concept of digital forests providing real-time data and insight from sensor networks and remote sensing

Abstract

This paper brings together perspectives on the future of forestry from academia, research and industry. A diverse group of people have been interviewed from the University of Canterbury, Toi Ohomai, Forest Growers Research (FGR), Scion, Port Blakely Ltd, Forest Protection Services Ltd and Forest Management Ltd. The results highlight the unprecedented potential of data and the power of a collective approach for shared learning and digital democratisation. The paper touches on what a forestry tech sector platform and service opportunity could look like for New Zealand. Finally, it explores what future work may look like due to mechanisation and automation and considers how support can be provided to the next generation of foresters joining the forestry sector.

Impact of digitalisation on forestry in NZ by 2030

Imagine if we knew every tree by name and could treat it personally. A network of trees providing health, growth and market data sensed in real-time. We could view our forest inventory, see our wood flows to different markets, spot secondary markets and waste streams, and create smart supply chains to trace and protect this natural resource to market. With digitalisation as the bonding force, by 2030 we have the potential to create a new value web for our forest-based industries in New Zealand.

Connecting to global megatrends by 2030, we will see more forests in urban environments and increased use of wood in these urban settings to reduce carbon emissions and enhance the overall wellbeing of communities. The full potential of trees will be realised through their role as a critical tool for climate change mitigation and as a natural regenerative solution to break society away from its reliance on fossil fuels. New Zealand will shift focus from logs as an export commodity to wood products with engineered and embedded value and bio-based products that are more sustainable and command higher worth in the hands of consumers. This will deliver new employment pathways at regional levels through distributed manufacturing and a demand for more digital-led skills.

Digitalisation will provide the ability to virtually see, hear, understand and manage our forests in ways that have not been possible before. The multiple dimensions that boundaryless data can provide to our forestry sector and nation will impact all levels and generate new jobs, new platforms and services, new ways of working, and new insights to drive and enhance productivity.

Forests rich in data will provide new value and insights

The forestry sector is collecting more data than ever before. The democratisation of technology, illustrated through the now widespread use of

unmanned aerial vehicles (UAVs), has highlighted the power of technology and data to the industry. Five years ago, forestry companies commonly had a spatial division comprising a single spatial analyst, for whom a key role was the production of maps. Today, UAVs are empowering a more diverse range of people to take part in remote sensing and mapping. With the additional influx of data from platforms, including UAVs, data science is the new skill in demand.

University of Canterbury lecturer in Geospatial Technologies, Dr Vega Xu, says that we cannot separate data from the technology, which means there is an increased need for data science. She notes that we have moved from megabytes of data to terabytes and working with new technologies creates a huge amount of data. There will be an increased need to develop methods for storing and maintaining this data in the future. Enhanced storage and cloud-based processing services will become more available and more cost-efficient.

Dr Xu says that large forestry companies will tend to adopt new geospatial technology first, as the cost for smaller forest owners is very high. However, those who can take advantage of the technology have the potential to unlock new value. Smaller forest owners are better off acquiring spatial data collectively.

Forest Management Group forest manager, Matt Cotterrell, believes that understanding forest growth as early in the rotation as you can enables much better decisions on the ground. He says that the sector will continue to become much more data-driven, and the longevity of data will span the forest's lifecycle. Trees will be monitored from the moment they are put in the ground, compared with today, where spatial data (such as LiDAR) is captured primarily for mature stands and currently provides limited use for early rotation stands.

Data will also drive greater accuracy and efficiency of common tasks. Alfred Duval, regional forester at Port Blakey Ltd, has described performing tasks using a lot more detail but with a lot less human input. He says that they are already performing what would have been

Figure 2: Scion unmanned UAV collecting LiDAR data over a pine forest

Figure 3: Mitchell Cooke and Alfred Duval from Port Blakely carrying out post-thinning quality control assessments with their UAV

a four-week task to manually review plots of young planted areas in a fraction of the time. They fly a UAV for two or three days, do two days of data processing and two to three days of 'ground truthing'. The output is highly accurate and stored for life. Port Blakey has seen huge value in the use of technology in the last three years, and Alfred Duval anticipates that this use will be perceptible in the crop and that the further value of using technology to assess stands at an age of 10 years, after thinning, or in 20–30 years at harvest time will be significant.

As well as utilising data such as visual imagery and point clouds for specific operations, digital data will also improve automation. With the increase in computing power in the past decade, the fields of machine learning and deep learning have made quantum leaps. Algorithms from these sub-fields of artificial intelligence (AI) require vast amounts of data, which can be used to train highly accurate models for solving many problems.

In forestry, deep learning and machine learning are being applied through operations such as seedling detection, land cover classification and phenotyping. These methods require vast amounts of training data to fulfil their potential. The challenges of working with such large bodies of data meaningfully, and compiling training datasets to deliver insight, need a collective industry approach.

Alfred Duval says there is an opportunity for data collaboration, especially for smaller forest owners, where participators' data could collectively flow into auto-detection models while keeping privacy paramount. This would provide a huge benefit for the industry, helping to democratise data and provide insights to foresters regardless of the size of their organisations.
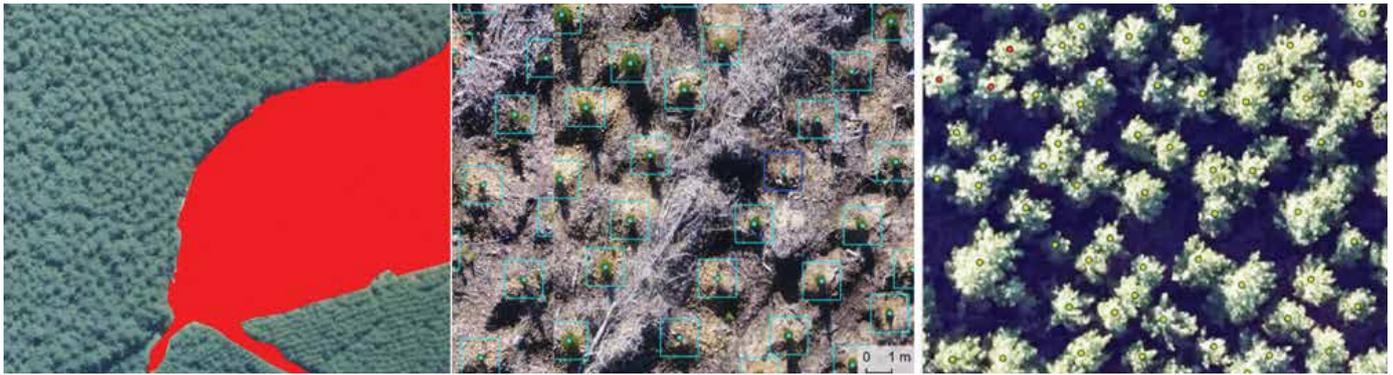
Figure 4: Deep learning (AI) models have been shown to work well for tasks such as mapping cutover (left), detecting seedlings (centre) and counting individual trees after thinning (right)

Scion remote sensing scientist, Dr Grant Pearse, believes that forestry companies will have data science teams as opposed to a data science person in the future.

University of Canterbury Associate Professor Dr Justin Morgenroth has highlighted the impact that technologies have in the hands of students. He says that they are creating LiDAR-based models using the iPhone 13. He notes that if developing LiDAR-based models can be made as easy as Apple has made everything else, then young people around the planet will know how to work with this technology in the future.

He also describes the intersection between LiDAR and drones, with photogrammetry as another potentially more accessible and cost-effective approach for foresters. There is potential to extract 3D structural data from our forest using something as familiar as photos. This provides information on forest structure without needing advanced data science or processing capability.

Supply chain connectivity will unlock new value chains

Data will continue to flow not just out of the forest but up and down the whole supply chain. This will support enhanced efficiency for existing commodity timber markets and shift into specialist, niche timber and bio-based product opportunities that could command new and higher values.

Dr Craig Morley, Associate Professor of Resource Management at Toi Ohomai Institute of Technology, believes this is an opportunity for Māori. From a Te Ao Māori perspective, forests, forestry and the management of the forest are seen in different ways. Embracing this difference has the potential to offer new value for Māori, which could then lead to higher value products to market or value protection.

Forest Growers Research Harvesting and Logistics programme manager, Keith Raymond, says the Wood First Policy will become more of a reality over the next decade. He notes that by 2030 the Wood First Policy will be more like law rather than lip service. Architects, engineers and specifiers will prioritise wood unless supply dictates other materials. He describes a future with smarter supply chains, smarter modelling and smarter buildings.

A smart supply chain also provides an opportunity to trace timber, with its associated unique characteristics (origin, genetics, treatment and management) through to market. There are now many tools available to the industry to enable the detailed tracking of silvicultural treatments and their impacts on the quality of the end product.

Forest Protection Services director, Kevin Ihaka, describes the value of digitalisation in validating and authenticating their work as forestry contractors. He points out that a contract management company usually sits between the contractor and the landowner to audit the work, representing 10%–15% of the contract value. If a contractor can advance to producing accurate, validated data to provide evidence for work done, that would take a step out of the supply chain and put more money back in the contractor's pocket.

Kevin Ihaka has also described this as a more transparent, data-led, 'warts and all approach', but he says there need to be industry protocols to ensure the approach is validated and authenticated. There is an

Figure 5: Digitalisation could offer greater value and protection to beautiful native podocarp forests through the ability to trace value through the supply chain

opportunity to standardise the methodology and for forestry contractors to become more technical and lift their game. In this approach, data-enabled contractors will move up the supply chain and take a greater share of the management role.

Indufor team leader of resource monitoring, Dr Pete Watt, describes the potential to take the data collected and transform it into useful information that drives new insight. Such information provides a real opportunity to re-think and improve workflows. It could enable better targeting of field resources, focusing on areas that may require intervention, and further enhance understanding of a site's growth potential. It could link tree locations with height information to give an immediate understanding of tree performance – even at the early establishment stage the data can provide a glimpse into the future.

Dr Watt says the detection model's scalability, transferability and accuracy are equally important. Forests are often widely dispersed, making it challenging to achieve timely coverage across large areas, and the industry is on the cusp of a real paradigm shift as innovation allows a move towards precision forestry.

Rise of data-driven companies, platforms and services

With this influx of data, we can also expect data companies to emerge to take advantage of the opportunity. These companies will look different from today's traditional forestry or forest management companies.

Dr Pearse says we could even see 'data-first' forestry companies, backed by large private equity that will bring a different perspective driven by algorithms to buy, sell and manage forests. Kevin Ihaka can also see the benefit of data service providers supporting forest management

Figure 6: UAV LiDAR point cloud colourised by individually segmented trees

with new platforms and services where data service providers might provide a valuable new service in the supply chain. They could deliver platforms where managers could upload data that would then return a count of the trees, plus any derived insight into health, pests and weeds. This could be done through an online portal with standardised outputs and services.

The forestry workforce of the future will be digital-led

Jobs and ways of working in forestry will look different, but people and the transition of the existing workforce will be paramount. The practicality of mechanising or automating tasks in the forest is a leap that not all foresters see the value in yet. In contrast, others can envisage a future that includes robot swarms and complete job transformation.

Keith Raymond says we will see multi-dimensional job roles, with a transition to becoming a supervisor of multiple automated machines. He notes that this will require a large effort in training and re-training and that we do not want to lose the skilled people we have in this expansion phase. However, we need these people to transition from the old roles into these new roles.
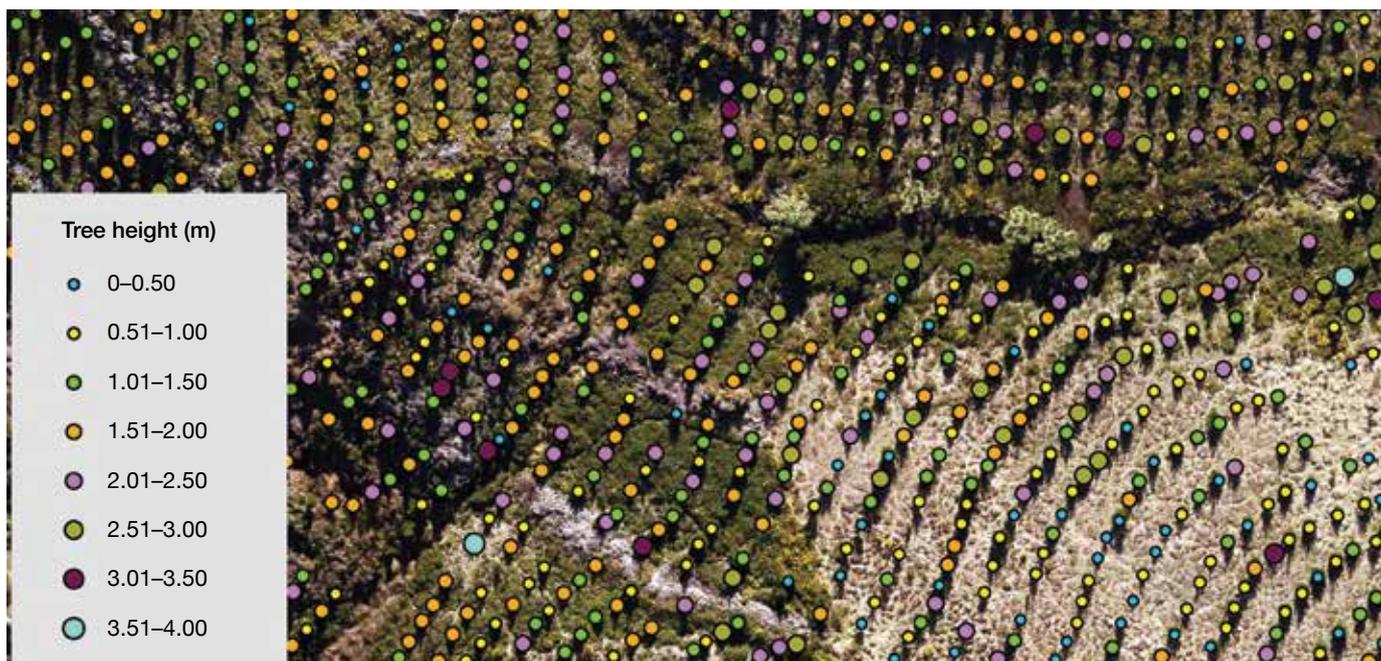

Figure 7: AI-derived tree locations and heights from fixed-wing aerial imagery (5 cm)

Figure 8: M-Planter in Kinleith Forest, Tokoroa. Multiple companies in NZ are currently using mechanised planting machines

Scion Human Factors scientists, Dr Richard Parker and Brionny Hooper, have outlined the importance of taking people out of the danger zone but keeping them in the loop. Dr Parker says the future is likely to look more mechanised than fully automated. He thinks we will see people controlling simplified machines, but emphasises it is good to have people in the forest. In this way, you have a workforce that knows the forest, is fit, can fight fires, keep an eye on security, and has a connection to the land and the local community that is part of the forest and environment.

Dr Parker also says we should consider a future where technology will enable much smaller, quieter devices instead of having large, expensive machines. For example, silviculture provides a good opportunity for smaller machines to solve smaller and more contained problems. There hasn't been a lot of technological advancement in tree pruning, but in the future there could be small, lightweight pruning machines with a novel power supply (battery pack on the ground beaming up to the device). The approach of taking a low-tech problem and applying an advanced technical solution could carry through to all tasks in nursery operations, planting and thinning.

Brionny Hooper says smaller machines will also change the structure of the workforce. She notes that currently contractors spend millions of dollars on machinery and must be very experienced to operate it.

New technologies, smaller in size, will achieve the same or better output for less money with safety at the forefront.

Dr Parker believes this change to smaller machines could deliver a big impact on the reputation of the forest industry. He says that several simple machines

Figure 9: An example of a smaller machine – a robot capable of moving from tree-to-tree to carry out forest thinning operations developed in collaboration with Scion scientists, FP Innovations and inFact Ltd

could be involved in an operation with less reliance on one big machine. It used to be like this with chainsaws – one person operated a lightweight personal machine, and if they were unavailable (due, for example, to illness) another operator could easily step in to replace them. Now harvesting gangs are often based on one big harvesting machine, and this machine needs to harvest one tree a minute to justify the capital cost.

Dr Morley can also envisage a future with more miniaturised terrestrial robots. He envisages swarm technology, multiple data sources and drones working as a team. The big challenge is sifting through the data to find value, but he believes we will advance through deep learning and AI to ask the right questions. There is a big role for academia to offer wider specialisations to set people up for the future directions of forestry.

Kevin Ihaka challenges the need to mechanise or automate certain tasks at all. He asks, 'Why mechanise planting?' He explains that emissions produced through this are a lot more than two planters on the hill. A machine has one person in it and is burning a lot of fuel. He challenges that if we start to think hard about carbon, there are some things we really shouldn't mechanise. The best option is always the one that supports people doing the job and we need to understand the supply chain and social costs of change better.

While Alfred Duval is open to trialling new approaches, he concedes it is hard to visualise how new technology will roll out. For him, the biggest issue is the practicality of mechanising some of the tasks. Port Blakey will trial mechanised planting systems next year, but have concerns about speed and quality. He says that a boot can get a lot closer to firm a seedling in the ground than a chunk of steel.

Keith Raymond believes that the rise of machines will open opportunities for New Zealand-based high-tech manufacturing industries – winch-assisted harvesting is a good example. This technology has now enabled four viable manufacturers in New Zealand alone. Over the next decade, technology will stimulate a New Zealand-based high-tech industry with a thriving export base. Adopting technologies from overseas is often not possible in the New Zealand market because of our steep terrain and large tree size.

Dr Pearse believes that we are more likely to be technology takers, not setters. He says that it takes an enormous investment to come up with something from scratch and that we need to look at places where there is the most value to be gained first. Determining which tree to thin and how to buck logs should not necessarily be a job for people. There is a lot of value to be gained from automation at those points and these are the most obvious places to begin.

Training our foresters of the future

Toi Ohomai Forest management tutor, James Broadley, outlines the need for more cloud-based learning

Figure 10: ClimbMAX Steep Slope Harvester manufactured by Trinder Engineers Ltd, Nelson (the first commercial NZ-made winch-assisted harvester)

platforms connected to experiential learning. He says that we need to consider on-the-job work experience as part of the qualification. Work experience and cloud-based training platforms go hand-in-hand. Students in the forest or processing facility could have a range of tasks to fulfil, and they could be sharing the videos, imagery and data back to the tutor to assess. This means less time spent in the classroom and more time spent in the forest, learning and practising skills (such as flying drones and gathering and analysing data). Increased digitalisation will be key to this improved learning pedagogy.

Dr Morley says COVID-19 has progressed the use of digital education solutions. However, there is still a lot of room for improvement in the design of education in a digital world, improving training and better supporting people into work.

Dr Xu believes that many students still see advanced algorithms used in analysing geospatial data, such as deep learning and machine learning, as a black box. She says that we need to teach students a wide range of topics, but the current curriculum for undergraduate study is reasonably fixed. To be more specialised for jobs, such as working with geospatial data, a student may consider further study for certain forestry specialisations.

The future of forestry for NZ

When considering the future of forestry for the country and combining this with the new value that data will offer, there is an untapped opportunity to look at our national forest estate as one.

Dr Pearse says there is an opportunity to have one digital view of our total forest. He says that this will answer a much broader range of questions. It will offer the potential for more insightful research that can happen faster and will drive decision-making. It will deliver immediate value for wood flows, wood supply and wood pricing. It would also help quantify the forest estate's aggregate value to the entire country.

He says this will become more important as the industry becomes more fragmented. With many smaller players entering tree planting, digital representations become essential to get information at the macro and micro levels.

As we continue into this period of rapid change led by technological advancement, two things are clear – we will have more trees in the ground than ever before, and the data undergrowth will be expanded with every tree planted. Once flourishing, this has the potential to spread and grow to deliver insight and exponential value to the forestry sector in New Zealand. The management of our forests and processing practices will be more efficient and mechanised, but people will still be an integral part of the picture. Workers in our industry will be safer and happier going about their work supported by more data and new technology.

Acknowledgements

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Te Uru Rākau – New Zealand Forest Service: looking towards the future

Jason Wilson

Abstract

Forests are acknowledged globally for the diverse benefits they provide. Planning strategically, both internationally and in New Zealand, includes considering how we can manage and develop forest resources for the benefit of present and future generations. It is a time of change, including considering how to respond to climate change. As we face the challenges of our time, taking a strategic approach, innovating, diversifying and working together is increasingly important. Te Uru Rākau – New Zealand Forest Service is working to plan strategically, support and advise the sector, improve services, and build a better future for New Zealand through forestry. This paper highlights what we see on the horizon and work underway to contribute to the future of forestry.

The value of forests and a global perspective

In early 2017, the United Nations released its *Strategic Plan for Forests 2017–2030* (UN, 2017) with the aim of promoting sustainable forest management and a vision that focuses on forests and trees providing economic, social, environmental and cultural benefits for present and future generations.

The UN Strategic Plan begins by acknowledging that forests are among the world's most productive land-based ecosystems and are essential to life on earth, including human wellbeing, sustainable development and the health of the planet. As explained in the UN Strategic Plan:

'Forests provide essential ecosystem services, such as timber, food, fuel, fodder, non-wood products and shelter, as well as contribute to soil and water conservation and clean air. Forests prevent land degradation and desertification and reduce the risk of floods, landslides, avalanches, droughts, dust-storms, sandstorms and other natural disasters. Forests are home to an estimated 80 per cent of all terrestrial species. Forests contribute substantially to climate change mitigation and adaptation and to the conservation of biodiversity.

When sustainably managed, all types of forests are healthy, productive, resilient and renewable ecosystems, providing essential goods and services to people worldwide. In many regions, forests also have important cultural and spiritual value' (UN, 2017, p. 3/24).

It also states, as set out in the United Nations forest instrument: 'Sustainable forest management, as a dynamic and evolving concept, is intended to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations.'

To support the benefits that can be realised from forests, the UN Strategic Plan sets out multiple global goals and targets on reversing forest loss, enhancing forest-based benefits, increasing sustainably managed forests and strengthening cooperation and partnerships.

Facing climate change

Four years later, the UN's Intergovernmental Panel on Climate Change released its 2021 report (IPCC, 2021) establishing the linkages between rising greenhouse gas emissions and increased severe weather events and rising temperatures. Amongst the findings and recommended mitigations in the IPCC's report, there is a reference to improved and sustainable forest management as a means of reducing emissions.

The central role for forestry in New Zealand's climate change response was highlighted in the 2021 report from the New Zealand Climate Change Commission (CCC, 2021), which provided advice to the New Zealand Government on its first three emissions budgets and direction for its emissions reduction plan.

The CCC's report acknowledged forestry as the only current option for removing carbon dioxide from the atmosphere at scale and its value in providing a long-term carbon sink, as well as making a number of recommendations. These included a national programme to establish more native forests, changes to the Emissions Trading Scheme (ETS) on the scale of forests planted, storing more carbon on smaller forest blocks, and a call for the Government to clarify the role of permanent exotic forests in reaching emissions targets.

In commenting on the significant role of forests in New Zealand, the CCC report states:

'Forests play a significant role in the history, culture, economy, and biodiversity of Aotearoa. Forests will play an important part in helping Aotearoa to meet emissions budgets and the 2050 emissions reduction targets, because they are the only way to remove carbon dioxide from the atmosphere ('emissions removal') that is currently available at scale.

Different types of forest will play different roles. New exotic production forests will be important to help meet emissions budgets and targets and to help sustain a thriving, low-emissions bioeconomy.

At the same time, establishing new native forests will be key to maintaining net zero long-lived greenhouse gases in the long term, balancing emissions from hard-to-abate sectors, while providing multiple co-benefits.

The role that emissions removals from forests play must be balanced with the need to make gross emissions reductions, and consider potential impacts of land conversion on rural communities and the broader food and fibre sector' (CCC, 2021, p. 315).

The CCC also highlighted the value of increasing native forests for providing an enduring carbon sink and set out recommendations to ramp up the establishment of new native forests to reach a recommended target of 25,000 ha per year. The report states: 'Native afforestation needs to start now to provide enough removals to maintain net zero long-lived greenhouse gas emissions beyond 2050' (CCC, 2021, p. 318).

Change presents challenges and opportunities

Along with driving the climate response, New Zealand's forestry and wood processing is undergoing change and transformation. The sector stands on the start of an exciting new era and the decisions and initiatives being taken now will shape the next 50 to 100 years. Not only will the seedlings we plant now grow into the forests that will benefit future generations, but planning and innovation will also drive our export revenues, pave the way for new products and services, open new markets, and build long-term economic growth and living standards. Our current decisions and direction will also be critical in providing New Zealanders with employment, training and career opportunities, as well as realising their aspirations for the future.

Overseas demand for New Zealand wood has been strong in recent years, growing by approximately 19% since 2017. The World Bank forecasts that global demand for wood and wood products is likely to quadruple by 2050. The World Bank says economic development, population growth and urbanisation are increasing the demand for forest products, which is projected to grow dramatically in the coming decades.

While demand for forestry and forest products is generally trending higher, changing global economic and political dynamics mean there is no guarantee of continuing and assured upward movement. Shipping capacity limits and rising costs have brought pressures for our forestry sector and economy, which is contending with volatility across commodity prices and issues with international market access.

New Zealand faces decisions about whether our businesses and economy continue to operate on the assumption of ongoing strong demand for our products, resources and services from our trading partners. There is risk in assuming that New Zealand's economy will not be immune to volatility in international markets, supply chains and transport pressure, shifting political and economic dynamics, and COVID-19, so we need to consider how to manage such risks and uncertainties.

Figure 1: Native tree (rimu). Climate Change Commission recommendations include ramping up the establishment of new native forests

While these factors present a challenge for New Zealand's economic growth, I have confidence in our forestry and wood processing sector and am keen to support it in work underway that is developing expertise, skills, human resources and innovation to meet our shared challenges.

COVID-19 has shown challenges and issues can arise suddenly and unexpectedly. Setting up for success now and in the future therefore requires both the sector and Te Uru Rākau – New Zealand Forest Service to adapt, plan and find solutions that are fit-for-purpose for emerging and changing trends.

Whatever the future holds, there is benefit in coming together as the forestry and wood processing sector to collaborate and pivot towards more diversification, innovation and transformation.

Working with the sector to build a better future

Since being established in 2018, Te Uru Rākau – New Zealand Forest Service's mandate has been to provide a policy and regulatory framework, leadership and direction for supporting the viability and sustainability of forestry, as well as optimising the potential of wood.

Our role is not just developing and supporting plans or policies for planting trees. It is about ensuring the right skills, resources, services and capabilities are in place to manage our forestry resources, promote investment and industry transformation, and deliver on the *Fit for a Better World – Accelerating our Economic Recovery* roadmap.

Central to this is successfully working with landholders, businesses, sector organisations, schools, the workforce, universities and research institutes, councils and local community groups across a range of programmes of work and joint ventures. Importantly, this includes Te

Uru Rākau – New Zealand Forest Service partnering with Māori. This will improve the quality of joint ventures and advice, help transform forestry, and enable Māori to realise their aspirations for their land.

Industry transformation and initiatives

Work underway in developing the Industry Transformation Plan (ITP) is aimed at moving forestry and wood processing from a commodity resource producer to one generating high-value jobs and low-carbon products by increasing domestic processing, lifting productivity, developing new onshore manufacturing, and generating new workplace skills and knowledge. By working together, taking a strategic approach, and innovating, we can lift the economic contribution from forestry and wood processing in New Zealand.

The ITP also aims to catalyse the production of new low emissions products and energy to support New Zealand's transition to net zero emissions by 2050. It envisions pathways and a foundation for developing and manufacturing high-tech, high-value products and biomaterial to replace carbon-intensive products currently used for fuels, heating, building and plastics. Not only are the objectives for export revenue and growth, jobs and prosperity for our regions, they are also about ensuring New Zealand meets its international climate change targets.

Joint initiatives underway that are helping plant the seeds of innovation and build towards transformation include:

- The Wood Fibre Futures Project – investigating opportunities to attract investment to produce liquid biofuel and products from wood residues, and generate export revenues, by replacing fossil fuels used by industry and the transport sector

- The Manufacturing Clusters initiative – developing opportunities to co-locate wood processing plants, and plants from other industries, to minimise waste, improve productivity and competitiveness, and process residues as a feedstock for secondary processing, electricity and heat production

- The Timber Design Centre initiative – facilitating greater use of timber in the construction of all building projects by providing information to a broad range of stakeholders to improve the ease of use of timber across the entire design, planning, construction and project management phases.

ETS Transformation Programme

Amendments to the Climate Change Response Act 2002 in June 2020 delivered a range of improvements to the ETS. These reforms aim to drive a substantial increase in afforestation, reduce operational complexity and improve ease of compliance for forestry participants. Our Forestry ETS Transformation Programme is working to deliver customer-centric services that simplify the user experience and support greater accuracy for current and future participants.

Forest Market Assurance Programme

The Forestry Market Assurance Programme is another important programme currently underway for Te Uru Rākau – New Zealand Forest Service and the Ministry for Primary Industries (MPI). This programme has the aim of strengthening the integrity of the forestry supply chain and is made up of registration for log traders and forestry advisors, and a proposed legal harvest assurance system. We are working with the sector and Māori to ensure these systems are fit-for-purpose for an evolving forestry and wood processing sector.

The purpose of registering log traders and forestry advisors is to ensure that logs grown in New Zealand are bought and sold in a way that is transparent and professional, with the quality of advice improving over time. MPI will hold the functions of the Forestry Authority to administer the registration systems. Te Uru Rākau – New Zealand Forest Service has been working with the New Zealand Institute of Forestry (NZIF) on establishing the Forestry Authority, and we are very appreciative for their feedback and support throughout this process.

The proposed legal harvest assurance system provides a legislative framework with measures in place to eliminate or mitigate the risk of regulated parties dealing with timber or timber products sourced from illegally harvested timber. This assurance is being increasingly asked for by our trading partners, and this system seeks to maintain New Zealand's competitive market access. It will also reduce the risk of illegally sourced timber being imported here. There is a worldwide trend where access to markets for products requires assurance of legality, and New Zealand's system will be a requirement for accessing many export markets.

Other upcoming workstreams and strategic intentions

The projects and programmes described above only highlight a few of the many streams of work we anticipate for the coming years.

We have a busy year ahead. At a high level, our many workstreams relate to our key strategic intentions set out MPI's Strategic Intentions 2021–2025 (MPI, 2021). These include:

- Unlocking the potential of the forestry and wood-processing industries

- Increasing planting of the right trees in the right places for the right purpose

- Strengthening our planning and advisory services

- Partnering with tangata whenua to transform New Zealand forestry and realise Māori aspirations

- Transforming the forestry components of the ETS

- Strengthening professional standards and the integrity of the supply chain

- Supporting rewarding careers in forestry.

Figure 2: Indigenous forest, Whanganui River

We look forward to the opportunity to update you in 2022 on work underway to enhance the planning and advisory services we provide.

Other important upcoming work this year will include considering the recommendations that come out of the Emissions Reduction Plan (under development at this time of writing this paper) and working within government to advocate for the sector as they deliver on these. The Emissions Reduction Plan will set out how New Zealand will meet its first emissions budget (2022–2025) and set the path towards meeting our long-term climate targets. It is anticipated to be a key step in the country's transition to a low emissions future. Forestry will have an important role to play, including through increasing indigenous afforestation.

Looking forward

The future for forestry and wood processing, in supporting New Zealand's economic growth and reaching climate and environmental goals, is challenging but also a future that presents opportunities.

Being successful in achieving these goals will mean ensuring the sector is built on the strongest foundations possible. Te Uru Rākau – New Zealand Forest Service is committed to continuing to work with industry partners to ensure the optimal use of our forestry and wood processing resources. Pathways include the integration of native and exotic forestry into existing land use practices, turning unproductive land into an asset, preventing erosion across rural areas, improving water quality and enhancing biodiversity.

The importance of responding to climate change and transforming to a carbon neutral forestry sector and economy cannot be understated. It is also about ensuring New Zealand can meet current and immediate export and local market demand for wood and wood products, and the sector as a whole has the right support, capability and flexibility to adapt and change to meet future trends, developments and challenges.

This is a key role for Te Uru Rākau – New Zealand Forest Service going forward. By working together with our industry stakeholders and partners, we can continue to build strong foundations for forestry and wood processing and a prosperous and environmentally sustainable future for New Zealand.

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A comparison of photogrammetric software for deriving structure-from-motion 3D point clouds and estimating tree heights

Volga Lipwoni, Michael S. Watt, Robin J.L. Hartley, Ellen Mae C. Leonardo and Justin Morgenroth

Abstract

The use of structure-from-motion (SfM) photogrammetry from unmanned aerial vehicles (UAVs) is becoming an increasingly popular means of characterising key forestry biophysical variables such as tree height. Despite the wide array of software that is available to process 3D point clouds from SfM, little research has investigated how the precision of predictions vary between software. This study compared the accuracy of tree height estimates for a young *Pinus radiata* trial (height range 1.4 – 6.1 m) obtained from 10 different software packages, which were used to derive canopy height models (CHMs) from UAV-acquired SfM point clouds. To ensure a fair comparison, the default parameters for each software were used without any data tuning.

Predictions of tree height ranged widely in terms of both precision (R^2 range: 0.61 – 0.86) and bias (mean bias error (MBE) range: 0.28 – 3.37 m). Height predictions with the highest precision and lowest bias were made using 3DF Zephyr (R^2 = 0.86; MBE = 0.58 m), Pix4DMapper (R^2 = 0.78; MBE = 0.28 m) and Maps Made Easy (R^2 = 0.85; MBE = 0.85 m). The availability of numerous software options provides choice to the user and this study helps to identify the best software for estimating tree heights from SfM-derived point clouds.

Introduction

Accurate forest inventory is critical for monitoring crop health and damage, optimisation of silvicultural operations and the prediction of forest volume and value. Traditionally, such information has been acquired through labour-intensive and time-consuming field inventory practices that measure or estimate key biophysical variables such as height, diameter, volume and density at various spatial scales. The use of remotely sensed forest data captured over different spatial and temporal scales has revolutionised inventory practices and has been used to supplement and sometimes replace traditional field inventory (Dash et al., 2015).

Light detection and ranging (LiDAR), a laser-based ranging system that measures the return time taken by a pulse of laser energy to travel between a sensor and target (Dubayah & Drake, 2000), has been widely used in forestry (De Gouw et al., 2020). LiDAR can be used to scan environments through either airborne (ALS) or terrestrial laser scanning (TLS) platforms. In forestry, the capability of LiDAR to penetrate the forest canopy has provided 3D data for the extraction of the most common biophysical variables at both the tree level and on an area basis. However, ALS is costly, and TLS is labour-intensive and time-demanding (Brede et al., 2017).

In recent years, airborne laser scanners have been miniaturised and can now be deployed from unmanned aerial vehicles (UAVs). UAVs have increased in popularity as an alternative to airborne and satellite platforms for collecting forestry data at local scales as they are inexpensive and easy to operate over relatively small areas (Mendes et al., 2015). For example, in New Zealand 83% of forestry companies have used UAVs to collect aerial imagery of their forests, while 17% have used UAVs to collect LiDAR data for their forests (De Gouw et al., 2020). There is a growing body of research into UAV laser scanning (ULS) for forestry applications, and this method often provides highly accurate estimates of many key forestry metrics (Hartley et al., 2020). ULS sensors are, however, still relatively expensive and therefore alternative methods for creating 3D models of forests have been developed and applied, including most notably structure-from-motion (SfM) photogrammetry (Wallace et al., 2016; Puliti et al., 2020).

Depending on the level of detail during image capture, 3D point clouds can be derived from UAV imagery using techniques that combine computer vision and photogrammetry, commonly referred to as SfM (Wallace et al., 2016). SfM photogrammetry is a method whereby multiple images are acquired from various camera viewpoints and then combined to form 3D models (Mathews & Jensen, 2013). SfM makes use of algorithms, such as scale invariant feature transform (SIFT) (Lowe, 1999), to find multiple key points in images, match images and create tie points (Mendes et al., 2015). The other key processes in the SfM

reconstruction workflow include bundle adjustment that leads to sparse point clouds, which is then followed by dense image matching to create dense point clouds using algorithms such as multi-view stereo (MVS) (Iglhaut et al., 2019).

A number of software packages have been developed to produce dense 3D point clouds from UAV imagery using SfM algorithms. These include cloud-based software packages, in which images are uploaded to servers, processed and downloaded as point clouds thereafter (e.g. Maps Made Easy and DroneDeploy). Desktop-based tools such as Agisoft Metashape (previously known as Agisoft Photoscan and hereafter referred to as Agisoft), Pix4Dmapper and PhotoModeler are alternatives to the cloud-based software tools. There are also a number of free and open source SfM software such as COLMAP. Among commercial packages, the most widely used software within forestry research are Agisoft and Pix4D (Lipwoni, 2020).

SfM photogrammetry acquired from UAVs is increasingly being utilised for forestry applications. SfM software packages have been used to process UAV data across a range of forest types (Lipwoni, 2020), including plantation forests (Wallace et al., 2016). Topographic models, including digital surface models (DSMs), digital terrain models (DTMs), normalised digital surface models (nDSMs) and canopy height models (CHMs), can be interpolated from SfM generated point clouds. These are subsequently used to estimate a range of biophysical variables, including tree heights (Mlambo et al., 2017), volume and biomass (Iglhaut et al., 2019), tree counts, and crown cover area (Gülci, 2019) and tree structure (Morgenroth & Gómez, 2014; Miller et al., 2015), as well as being used for individual tree delineation (Maturbongs et al., 2019).

Previous research has shown that the image acquisition process is an important factor for producing high-quality 3D point clouds from photogrammetric data (Dandois et al., 2015; Frey et al., 2018). However, once acquired, images can be processed by numerous SfM software packages and the selection of the most appropriate tool has become an important issue for most projects (Turner et al., 2013). Different factors (such as ease of use, accuracy, processing time, precision and cost) are likely to influence software choice.

Despite the clear need to understand how software choice impacts results (Forsmoo et al., 2019), few studies have compared the performance of different software packages for assessing forest biophysical variables. Using UAV imagery from a Douglas-fir plantation, recent research examined the effects of tree segmentation and algorithms that generate point clouds on tree

Figure 1: Location of trial plot at Scion in Rotorua. The area of interest is bounded on the map in purple and the layout of ground control points (GCPs) is marked with yellow crosses. The upper right inset shows a GCP

identification and the precision of height predictions (Maturbongs et al., 2019). This study found significant differences in estimates of tree height between images processed using Agisoft and Pix4Dmapper.

In this study, we expand the scope of these comparisons beyond the two most widely used SfM software for predictions of tree height. Height measurements and SfM models from a UAV were obtained from a trial of the widely grown plantation species *Pinus radiata* D. Don (radiata pine) that covered a height range of 1.4 – 6.1 m. Using these data our objective was to compare the precision and bias of predictions of tree height made using 10 SfM software.

Materials and methods

Study site

The study area was located at the New Zealand Forest Research Institute Limited (Scion) tree nursery in Rotorua, New Zealand (Figure 1). The flat site measured 55 m x 110 m and was planted with *P. radiata* in rows with a spacing of 2.5 m x 3 m. The grass at this site was regularly mowed. Following a recommendation from a previous study (Hartley et al., 2020) this site was selected as acquisition conditions were optimal. Through eliminating variation attributable to terrain and understory development this study was able to examine the influence of different SfM software on predictions of tree height.

Feature annotations of the 610 individual trees inside the area of interest were created manually using ArcGIS Pro version 2.5.1 (ESRI Inc., 2019). The RGB orthomosaic (Figure 1) and field data were used as the reference for locating and labelling the individual trees. These feature annotations were exported as shapefiles and used as input in the tree height extraction.

Field data collection

Field measurement of tree heights was undertaken between 17 and 29 March 2019. Heights of individual trees that were ≤ 5 m were measured and recorded using a survey-grade height pole with a resolution of 1 cm. A Vertex IV hypsometer (Haglöf Sweden AB, Långsele,
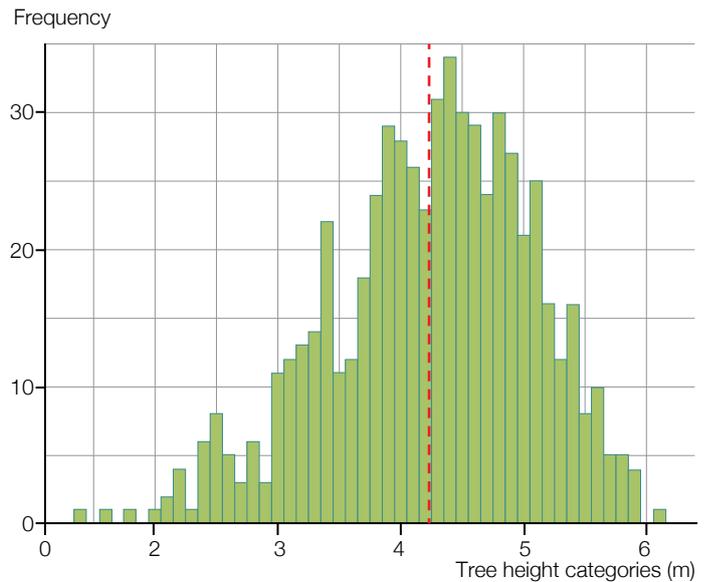

Figure 2: Distribution of field measured heights

Sweden) with a resolution of 10 cm was used for measuring trees over 5 m. The Vertex IV has been found to have a relative error of between –0.19% and –1.23% for tree heights in coniferous species (Stereńczak et al., 2019). The measured tree heights ranged from 1.4 – 6.1 m with a mean of 4.24 m (Figure 2).

UAV data acquisition

Data was captured by a DJI Phantom 4 Pro (DJI Ltd, Shenzen, China) using the integrated DJI RGB camera with a 1" CMOS 20-megapixel sensor. The camera creates an image of 5472 x 3648 pixels and has a field of view of 84 degrees. A flight plan was created considering key flight parameters, including image overlap, ground sample distance (GSD), altitude, flight line spacing, orientation, overflight and the location of the take-off and landing. The flight was undertaken on 4 April 2019 at 3pm using the Map Pilot flight control app (Drones Made Easy, San Diego, CA, USA). The flight was carried out at an altitude of 60 m above ground level, providing an average GSD of 1.6 cm. The image overlap was set at 85% forward and 80% side overlap. A total of 422 RGB images were captured in JPEG format.

Table 1: SfM software selected for the study

Software	Version	Platform	Availability
Pix4Dmapper	4.6.3	Desktop-based	Commercial
Agisoft	1.5.2	Desktop-based	Commercial
COLMAP	3.5	Desktop-based	Free and open source
RealityCapture	1.0.3 10393RC	Desktop-based	Commercial
UASMaster	9.0	Desktop-based	Commercial
3DF Zephyr	4.519	Desktop-based	Commercial
Maps Made Easy	N/A	Web-based	Commercial
DroneDeploy	N/A	Web-based	Commercial
ContextCapture	10.17.0.39	Desktop-based	Commercial
PhotoModeler	Premium 2019.1.2	Desktop-based	Commercial

Table 2: Variation between software in the number of points, point density and point spacing (software are sorted in descending order regarding above ground point density)

	Total number of points (x 10³)		Point density (pts m⁻²)		Avg point spacing (m)
	Ground	**Above ground**	**Ground**	**Above ground**	**Ground**
ContextCapture	65,653	37,144	3,402	2,042	0.02
Pix4Dmapper	4,447	5,754	239	300	0.06
3DF Zephyr	557	5,436	29.5	283	0.18
PhotoModeler	273	4,167	14.6	216	0.26
Agisoft	3,785	2,826	199	179	0.07
RealityCapture	5,224	2,461	271	150	0.06
Maps Made Easy	3,991	2,321	218	122	0.07
COLMAP	2,917	1,655	152	94.7	0.08
UASMaster	3,764	358	195	26.6	0.12
DroneDeploy	608	185	32.4	9.79	0.18

The imagery was georeferenced using eight GCPs that were distributed across the study site, with the majority concentrated around the trial plot and a few close to the permanent structures within the nursery (Figure 1). These points were surveyed on the day of the flight using a Trimble Geo7X handheld GPS unit (Trimble Inc, Sunnyvale, CA, USA) with a Trimble Zephyr Model 2 external aerial. GPS fixes were captured over each ground target by averaging a minimum of 180 point fixes captured over a time period of approximately three minutes. The resulting root mean square error (RMSE) of the collected points was 0.03 m.

SfM software

Ten SfM software were used to generate point clouds from the UAV images. Among these, nine were commercial and one was free and open source software (Table 1). DroneDeploy and Maps Made Easy are web-based, while the remainder were desktop-based software. All desktop software were installed on a 64-bit Windows 10 enterprise desktop computer with an Intel(R) Xeon (R) CPU E5-1650v3 @ 3.50GHz, 128 GB RAM and an NVIDIA QuadroM4000 73,638MB graphics card.

For each of the software assessed, the processing of the point clouds generally followed four key steps: loading of the images, feature extraction, feature matching and point cloud reconstruction. GCPs were added to each model in line with the specified procedure for the respective software. The resultant point clouds were exported in LAS format. The default settings for all parameters were adopted within each software during data processing. While the workflows across the software were comparable, there were some differences. The specifics of these differences are not included here, but are described in Lipwoni (2020).

Web-based software

Maps Made Easy is a pay-as-you-go service that provides systematic instructions on its webpage requiring little customisation of processing parameters. Once a user account was created, images were uploaded and export parameters were selected. Maps Made Easy did not have provision for loading GCPs, and an image location verification procedure using a 'Georeferencing tab' was undertaken instead.

DroneDeploy cloud processing can be carried out using two possible modes: Terrain and Structure. The former, which was chosen for this study, is best suited for areas with small differences in elevation and the latter for areas with large differences in elevation. After uploading images and GCPs, images were reviewed with the aim of excluding blurry or over-exposed photos. The automatic GCP detection procedure enabled accurate location of individual GCPs. Image processing commenced once final upload was confirmed.

Desktop-based software

One challenge of comparing desktop-based software was that each had different parameter settings and processes. The optimisation of parameter settings was beyond the scope of this study, but has previously been studied (Maturbongs et al., 2019; Hartley et al., 2020). Instead, we chose to run the software with default processing parameter values.

Workflows for the desk-based commercial software consisted of between three and four main processes as detailed in user manuals (e.g. Agisoft, 2019). The initial processing step produced sparse point clouds without spatial reference. Thereafter, GCPs were used to optimise image alignment and orientation of the sparse point clouds. Each of the eight GCPs were located and manually marked in at least five images. An iterative process of aligning images was adopted for best results.

After optimisation and further alignment, the final process was dense point cloud reconstruction for each software package.

Point cloud description

The point cloud creation process resulted in point clouds with varying densities (Table 2) that were determined using the 'lasinfo' function in LAStools (Isenburg, 2019). Ground point density averaged 475 pts m^{-2}, while the average above ground point density was 342 pts m^{-2}. ContextCapture produced point clouds with a markedly higher density than that of any of the other nine software (Table 2), with ground point densities of 3,402 pts m^{-2} and above ground point densities of 2,042 pts m^{-2}.

Extracting tree heights

The dense point clouds were processed using LAStools version 190404 (Isenburg, 2019). LAStools was initially designed for LiDAR point cloud processing, but has increasingly been used to process UAV-derived point clouds (e.g. Mlambo et al., 2017). Each point cloud was tiled at 100 m resolution with 10 m buffers, except for the ContextCapture dataset. As the file size from ContextCapture was very large the point cloud was tiled at 10 m with 2 m buffers. All the datasets were then denoised using 'lasnoise' twice – with the first step parameters of 0.25 m for XY, 0.5 m for Z and 32 minimum isolated points, while the second step parameters used were 0.25 m for XY and Z and eight minimum isolated points.

The 'lasground_new' function was used to classify ground points with a step size of 10 m. Once ground classified, the 'lasheight' function was implemented to derive the normalised heights for each point. Lastly, the tile buffers were removed using 'lastile' then 'las2las' was used to merge the tiles into one normalised height LAS file. This normalised point cloud was then input into R, in which the shapefile of individual tree crowns was used to segment the point cloud into areas representing the individual trees. Tree heights were then derived by iterating through each individual tree segment and creating a CHM using the 'grid_canopy' function from the LidR library (Roussel et al., 2018) The highest point inside each individual tree segment was extracted as the tree height. The R software version 3.6.0 was used in these analyses (R Core Team, 2020).

Statistical analysis

The accuracy of SfM-derived tree heights was evaluated by comparing them to field measured heights. Statistical analysis was carried out using standard descriptors commonly used for similar methods in other studies (e.g. Torresan et al., 2018), and included the coefficient of determination (R^2), root mean square error (RMSE) and mean bias error (MBE). These metrics were calculated using the following equations:

$$R^2 = \frac{\sum_i (\hat{y}_i - \bar{y})^2}{\sum_i (y_i - \bar{y})^2} \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \qquad (2)$$

$$MBE = \frac{1}{n} \sum_{i=1}^{n} y_i - \hat{y}_i \qquad (3)$$

where y_i represents field measured heights, $\hat{y}_i$ represents predicted heights from UAV point clouds, $\bar{y}$ is the average of the observed values and n represents the sample size. The percentage RMSE (RMSE%) was also determined through expressing RMSE as a percentage of $\bar{y}$ as RMSE% = 100 (RMSE/$\bar{y}$).

Analyses were undertaken using R to determine if the software precision was significantly related to the point metrics described in Table 2. Using a linear model, we fitted correlations between the software precision (as described by R^2) and the measures of point density. The correlation coefficient and significance were extracted from these five correlations.

Results

Overview

Plots of measured height against predictions from all 10 software packages are shown in Figure 3. All software generally under-predicted tree height across the range, but the extent of this bias varied widely.

The software could be categorised into three general groupings (Figure 4) based on precision (R^2) and bias (MBE). Tree height predictions with high precision and moderate bias were made by Pix4DMapper, 3DF Zephyr, Maps Made Easy, Agisoft and to a lesser extent ContextCapture (Figure 4). Software which predicted height with moderate precision and moderate bias included RealityCapture, COLMAP and PhotoModeler. DroneDeploy and UAS Master predicted height with high precision but high bias (Figure 4).

Software prediction precision, bias and accuracy

There were moderate-to-strong linear correlations (R^2 = 0.61 – 0.86) between predicted and measured tree height for all software (Figure 4). The software with the highest correlation was 3DF Zephyr (R^2 = 0.86), followed by Maps Made Easy and ContextCapture (R^2 = 0.84 – 0.85). COLMAP, the only free software, yielded predictive precision of R^2 = 0.69. Maps Made Easy was the most precise web-based application (Figure 4). In terms of accuracy, as measured by RMSE, values ranged from 0.57 m – 3.43 m (RMSE% = 13.5% – 80.9%), with Pix4D having the best accuracy, followed by 3DF Zephyr and Maps Made Easy. Height predictions from DroneDeploy and UASMaster had the poorest accuracy.

All software under-predicted height for the entire height range, with the exception of Pix4D in which predictions for very tall trees were over-predicted (Figure 3). Tree height prediction bias ranged between MBE = 0.28 m – 3.37 m. The least biased predictions were made by Pix4D (0.28 m) and 3DF Zephyr (0.58 m) (Figure 4).
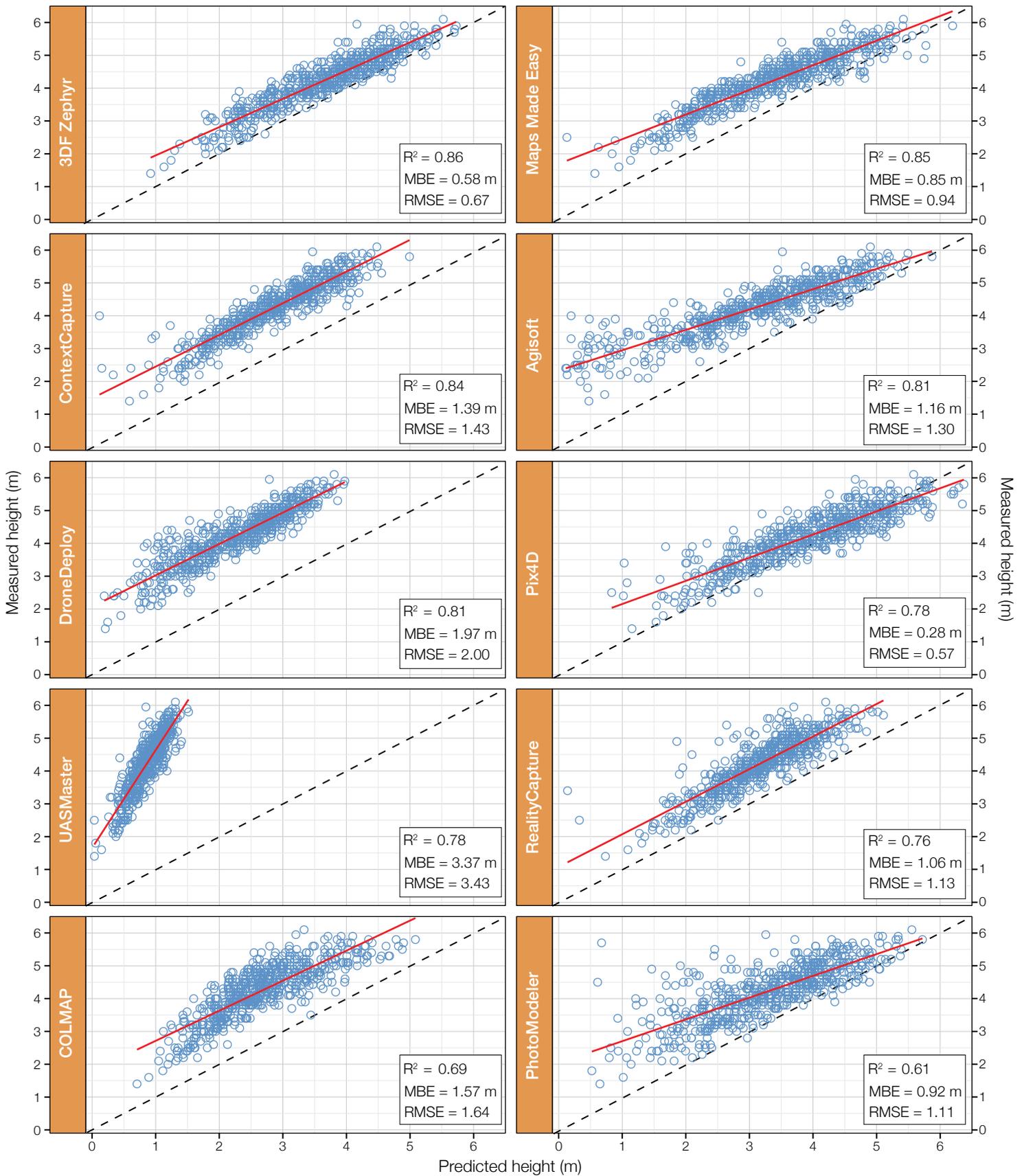
Figure 3: Linear regression of field-measured heights against predicted heights from the 10 software. The solid red line shows a linear regression fitted to the data and the dashed line represents the 1:1 relationship. The panels are sorted from panel (a) – (j) in order of descending values for the coefficient of determination (R²) between predicted and measured height (shown bottom right). Also shown bottom right is the mean bias error (MBE) and root mean square error (RMSE)
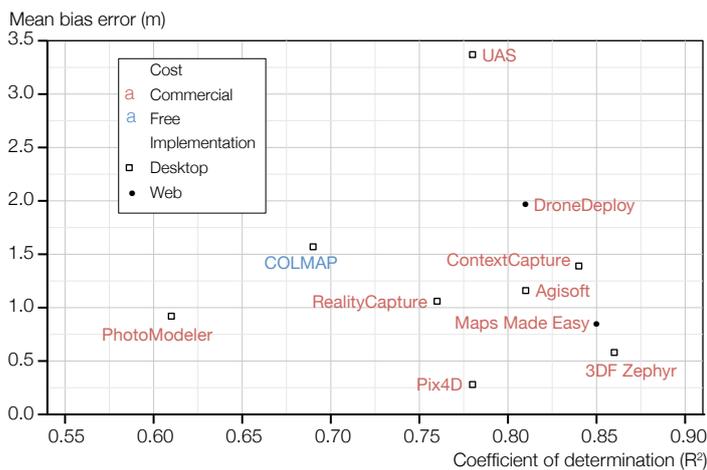
Figure 4: Variation in mean bias error and the coefficient of determination for predictions of height made by the 10 software

In contrast, height predictions from DroneDeploy (MBE = 1.97 m) and UASMaster (MBE = 3.37 m) were the most biased.

Relationships between model precision and point density

Regressions were constructed between model precision, as described by the R^2, and the five metrics describing the number of points and point density (see Table 2), to determine if model precision was significantly affected by point density. These five relationships were weak and insignificant, with P values ranging from 0.18 – 0.45 (data not shown).

Discussion

Results from this study clearly show the quality of tree height predictions using SfM is dependent on the software used to process the point clouds. In terms of precision, accuracy and bias, Pix4DMapper, 3DF Zephyr and Maps Made Easy out-performed all other tested software using default values. Predictive precision from the 10 software ranged from moderate-to-high and although all software underestimated tree height the extent of this bias ranged widely. This variation shows that software choice represents a considerable source of error in predictions of tree height using SfM.

Predictions from the most accurate software (Pix4D Mapper and 3DF Zephyr) were broadly comparable to previous studies that have used SfM to predict tree height. Previous research demonstrates a wide range in accuracy and precision between studies, with the RMSE% ranging from 1.89% to 19.4% and the coefficient of determination, R^2, ranging from 0.21 to 0.99 (Lipwoni, 2020). Our predictions were at the more precise end of the coefficient of determination range ($R^2 = 0.86$), but the less accurate end of the RMSE% range (13.46%).

The percentage RMSE was comparatively inaccurate as predictions were made for smaller trees than those typically studied, which has been shown to inflate RMSE% values (Hartley et al., 2020). This occurs

as an equivalent RMSE will be a greater percentage of the mean for a smaller than a taller tree and our results generally show high RMSE for the smaller trees in the study. For example, there was convergence between the fitted prediction line and the 1:1 line with increasing tree height for the three most precise and accurate software (Pix4DMapper, 3DF Zephyr and Maps Made Easy, Figure 3), indicating that RMSE was on average higher for smaller trees. When height error was expressed in absolute terms, our predictions (RMSE = 0.57) were somewhat less accurate than other studies that have found estimates from SfM to be within 0.5 m of field-measured heights (Lipwoni, 2020).

Default parameter settings were used to allow software to be fairly compared and to realistically assess the quality of predictions that will be available to most users who do not typically tune software. However, it is worth noting that less biased predictions may be obtained when software settings are optimised. Previous research has found that by fine-tuning the 'dense point quality' and 'image alignment' parameters, the percentage of tree heights accurately measured could be improved by 13% (Maturbongs et al., 2019). The same study found that Pix4D could also be optimised through manipulation of the point density and image scale parameters, with an increase of 10% in the percentage of tree heights accurately measured.

In practice, high values of MBE are unlikely to be as concerning as a low coefficient of determination because high MBE can be corrected using a calibration dataset that includes tree measurements. Predictions can be adjusted to correct for the bias, either within the processing software or through use of a linear regression to re-scale predictions before large-scale height prediction is undertaken. However, ideally predictions should have both low bias and high precision to avoid these tuning operations which are time-consuming for users of the software.

Previous research has shown that SfM point clouds cannot describe the underlying terrain as accurately as laser scanning, particularly when captures are made over undulating terrain and/or in dense forests with undergrowth (Wallace et al., 2016). However, as the studied site was very flat with no understory, previous research has found the integration of a DTM derived from a high-density UAV LiDAR capture (SfM-UTM) did not improve height predictions (Hartley et al., 2020). Previously documented height predictions for this dataset made by Pix4D using both SfM and SfM-UTM (Hartley et al., 2020) show little variation in precision ($R^2 = 0.80$ vs 0.81) and a slight deterioration in bias using the SfM-UTM (MBE = 0.4 vs 0.45 m).

Further research should compare the performance of SfM software at predicting tree dimensions in stands with more developed and diverse understory weed species that encompass a greater range in terrain. Ideally, this research across more challenging and realistic environments should identify the conditions under which it is most efficient to combine a LiDAR DTM with the SfM point cloud.

While this study focused on the quality of height predictions, there are a number of other criteria against which SfM software can be compared. Previous research has compared more qualitative aspects of SfM software, including the financial cost, computational cost, ease of use, the range of data products available, the degree to which software can be customised, and the benefits and drawbacks of cloud versus desktop applications (Brach et al., 2019; Forsmoo et al., 2019).

In this study commercial desktop-based software were generally found to have a faster processing time than freely available software. Data was processed in less than three hours using Agisoft and RealityCapture and less than four hours using Pix4D, UASMaster and 3DF Zephyr. COLMAP took almost 21 hours to complete processing, possibly because the processing algorithms cannot be parallelised (Turner et al., 2013). Out of the four processing steps (see SfM software section in *Materials and methods*), point cloud reconstruction accounted for 48% to 92% of the total processing time for all desktop-based software.

The web-based software Maps Made Easy and DroneDeploy completed point cloud processing after approximately six hours. Although the process was longer overall for the two web-based applications, less than 15 minutes was required to load the images and set up the project, with the remainder of the time used for cloud-based processing. The benefits of these two web-based solutions include moving the computational load of the process to the cloud, reducing the load on the user's own machine and allowing for multiple projects to be processed simultaneously (Brach et al., 2019).

The price of the SfM software varied greatly. The clear advantage of the open source software packages, such as COLMAP, are that they are available at no cost to the user. Monthly costs of the commercial software ranged from free for small projects (Maps Made Easy, 3DF Zephyr), to between USD302 and USD910 for RealityCapture, depending on the licence level purchased. Point cloud processing is only available as a pay-as-you-go option with Maps Made Easy. This is a points-based system, with points calculated on the density of the resulting output in gigapixels. Projects are free for models of up to 250 points or points can be purchased in bulk as a form of credit at a cost ranging from USD7.99 for 300 points up to USD669 for 50,000 points. As an indicator of cost, a model of the 55 m x 110 m trial area described in this study would cost around 360 points in Maps Made Easy.

Conclusions

This study compared the performance of 10 SfM software for tree height prediction from 3D point clouds. Using default settings, predictions from Pix4D, 3DF Zephyr and Maps Made Easy were the most accurate and precise. Software choice had a clear impact on the quality of tree height estimates and consequently represented a major source of potential error in predictions of tree height. The wide variation in point density and the number of points between the 10 different SfM point clouds was not significantly related to the precision of predictions. Although this study clearly shows the utility of SfM for predicting tree height, practitioners and researchers should be judicious in their choices when selecting software for this purpose.

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From plus-tree to genomic selection – new developments in breeding strategy at the Radiata Pine Breeding Company (RPBC)

Mark Paget

Abstract

In genetic improvement programmes, breeding strategies are reviewed periodically as breeding populations advance, research gains new insight and the latest technologies are ready to be operationally implemented. The Radiata Pine Breeding Company (RPBC) strategy was reviewed in 2018 and this paper provides an update on the latest developments at the RPBC as the company begins to implement genomics to better inform tree selection decisions.

Introduction

From its origins in a relatively small geographical region in California and the islands of Cedros and Guadalupe off the coast of Mexico (Figure 1), *Pinus radiata* D. Don has proved remarkably well adapted to a range of growing conditions in temperate regions of New Zealand, Australia and Chile, producing a versatile general purpose timber.

The breeding programme for *Pinus radiata* in New Zealand began in the early 1950s and continued for several decades under the direction of the publicly funded New Zealand Forest Research Institute (NZFRI). The Radiata Pine Breeding Company (RPBC) was formed in 2001 and the programme became more commercially focused, developing a seed certification scheme with revenue generated by royalty collection. Today, the programme holds an integral place in the forestry value chain (Figure 2). There are 16 shareholder members from New Zealand, New South Wales and Tasmania who range from germplasm producers and growers through to wood processors.

The value of improved genetics on forest productivity has been demonstrated (e.g. Kimberley et al., 2015). Unlike many commercial breeding programmes, however, there is no vertical integration of the programme itself. The RPBC has limited control of germplasm deployment, suggesting that the transfer of genetic gain from the breeding population to the production forest may be sub-optimal.

With 1.7 million ha of stocked forest plantation area in New Zealand in 2020–21, 1.5 million ha were radiata pine alone, with 100,000 ha of Douglas-fir the next most important species (NZFOA, 2021). This inevitably raises concerns over a potential over-reliance on a single

Figure 1: *Pinus radiata* native to coastal California and Mexico (Guadalupe and Cedros Islands). Monterey and Año Nuevo provenances have been found to be best suited to NZ conditions. Source: Burdon et al., 1997

species for softwood production and therefore demands consideration of risk mitigation when developing selection strategies and future breeding goals for the RPBC breeding programme.

After years of promise, the use of genomics as a selection tool is starting to be implemented in the RPBC breeding programme, which is a significant milestone given the motivation of increasing the rate and delivery of genetic gain. It therefore seems an appropriate time to review the progress of the RPBC from a historical context, as well as outlining several recent developments to advance breeding strategies for radiata pine.
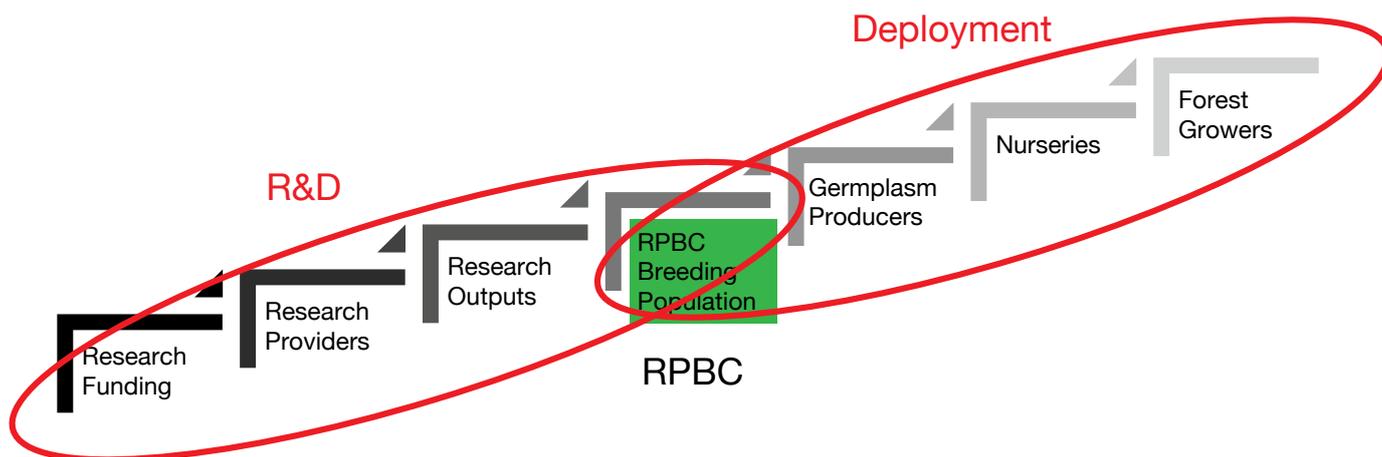
Figure 2: The RPBC's place in the NZ forestry chain

Breeding objectives

Genetic improvement is considered to be a technological development. Breeding programmes organised to drive these developments target the reduction of costs through new or improved breeding processes or increasing the value of the output. In tree breeding, for example, the objective might be to increase forest productivity in quantity or quality or improve system sustainability.

The perspective from which the objective is quantified will determine who benefits (e.g. the breeder, seed supplier, forest, sawmill, the industry or society in general). The RPBC's objective has been developed from the perspective of the forest industry as a whole. The breeding objective of the RPBC is reviewed periodically. The most recent was in 2019 (Woolaston, 2019) and places most emphasis on volume and timber stiffness. However, it also includes branching, and corewood density projected to rotation age, which for radiata pine in New Zealand is currently on average around 28 years (NZFOA, 2021).

For tree selection, it is generally considered ideal to include all traits that will contribute (directly or indirectly) to the breeding objective. In practice, a compromise must be met so traits are restricted to those that have potential for genetic change and those which are cost-effective to measure within a finite set of resources. Economic values for traits that directly contribute to the breeding objective (defined as the effect of a marginal unit change in the genetic level of a trait on the breeding objective when all other traits are kept constant) have been derived using a bio-economic model.

Each selection trait is weighted appropriately to maximise response in the objective, considering trait phenotypic and genetic parameter estimates. These weights are then combined with their estimated breeding values (EBVs), derived from trait measurements in field test trials, in a selection index (expressed in $NPV (net present value)/ha), which is used to rank individual trees accordingly.

Traits that contribute to the selection index and are measured in test trials at selection age (five to eight years after trial establishment) include diameter at breast height (DBH), straightness of stem, branching frequency, corewood density and acoustic velocity to obtain a predicted modulus of elasticity (PME). All have low (~0.20 DBH) to moderate (~0.50 density) heritabilities. *Dothistroma septosporum*, a heritable trait, is also assessed. It is not currently included in the breeding objective but can be used as a threshold trait in parent selection.

Although the breeding population generally works with a single selection index, there are opportunities at the deployment step for seed/clonal providers to use deployment indices to emphasise other priorities for foresters (e.g. to put more influence on growth, or trade-off growth for improved log and wood properties, or target a particular end-use such as carbon capture biomass)).

Selection strategies

Early generations

At the start of the breeding programme, intensive selection of individuals from established forest stands to establish clonal seed orchards was based on observed phenotype ('plus-tree' selection). Subsequently, the screening of large numbers of progeny from less intensively selected trees by the establishment of test trials was used to identify open-pollinated (OP) progeny-tested parental candidates to form the next breeding generation.

Further collection, testing and selection took place over several decades, which has formed the genetic base for today's breeding population (for more details on these early developments see Shelbourne et al., 1986; Burdon, 1992; Burdon et al., 2008). For a comprehensive commentary, including a summary of publications and abstracts from tree breeding research in New Zealand, see Shelbourne and Carson (2019).

Stratification of the breeding population

The initial focus had been on the development of seed orchard parents and regionally adapted breeds. In a revised strategy by Shelbourne et al. (1986), the typical breeding population hierarchy was more clearly defined, with a production population underpinned by the breeding population (e.g. see Figure 3). The emphasis was still on progeny testing, but population structure had been refined and based on non-specialist 'Main' (non-regionalised) and specialised 'Elite' populations.

Selection emphasis up until now had been on growth and form, but by 1990 the importance of including wood properties was recognised. With the introduction of control-pollinated (CP) seed orchards from 1984, opportunities were identified to deliver specialist 'breeds' from elite parents and the production of deployment seedlots for specific end-uses (Carson, 1996; Jayawickrama & Carson, 2000). There were two key developments during these decades that form the basis of the RPBC breeding strategy as it is currently implemented:

- **Clonal testing**
  The value of cloning of individuals within families was recognised, to improve selection precision and therefore to increase genetic gain (Shaw & Hood, 1985). Kumar (2006) demonstrated that clonal performance as cuttings appeared to be an adequate predictor of progeny seedling breeding values, and it was recommended that seed orchard selection could be made directly on this performance without recourse to progeny testing.

- **Forward selection**
  Breeding strategy in tree breeding was initially based on backward selection of parents based on their progeny performance. Studies were indicating that there were advantages in trading off the longer generation intervals in backward selection, with lower selection accuracies in the forward selection of parents based on their own performance (as individuals or clones).

Based on these developments, the strategy evolved once again (Shelbourne et al., 2007; Dungey et al., 2009). The breeding population proposed was stratified further and was comprised of a large OP Main breeding population (MP) of two sublines to better manage genetic diversity (inbreeding that occurs is contained within sublines). The MP would be managed in discrete generations (i.e. all activities on the MP are completed once over a discrete phase, for example, crossing through to trial measurement and parent selection and no overlap of breeding activities).

A much smaller CP Elite production population (EP) was also proposed made up of two sublines, with clonal testing and selection implemented as a 'rolling front' (breeding activities carried out annually, for example, selection, pollination, test trial establishment
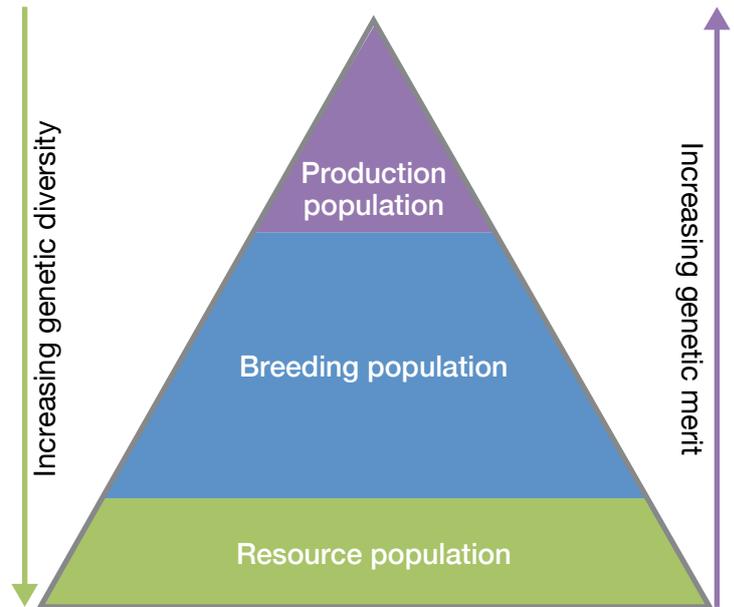

Figure 3: An illustration of breeding population structure with the production population as the top tier (including deployment genotypes), carried by the breeding population, with the genetic 'archive' conservation resource at the base

rather than as discrete generations). The best material from the EP could be propagated by grafting and being established into a seed orchard as seed deployment parents. The actual RPBC implementation is outlined in *The Breeding Management Plan* (Jefferson, 2016) and had some commonalities with what had been proposed but was not complete.

Simplifying the structure of the breeding population

After an RPBC review in 2018 (RPBC, 2018), it was decided to simplify the population structure and collapse the Elite and Mains into a single breeding population. Sublines are no longer maintained. Genetic diversity is maintained by selection algorithms, which maximise gain within certain constraints to control relatedness (e.g. Kinghorn, 2011). With the production of clones from juvenile cuttings becoming routine for nurseries, all testing is now based on vegetative clones as selection candidates.

Breeding trials are established annually in commercial forest stands on five to eight sites per year of 3–4 ha across New Zealand, NSW and Tasmania. An 'Individual Tree Model' calculates EBVs using BOLT software (Theta Solutions LLC, 2021) which also provides a platform to implement single-step genomic evaluations to obtain genomic estimated breeding values (GeBVs) for genomic selection (GS).

Breeding generations are overlapping, and new parental breeding and orchard candidates are selected from the top-performing clones based on their EBVs. These are retrieved from trial sites as scions (and pollen) and grafted for establishment into seed and/or breeding orchards.

Implementation of genomic selection

A 36k SNP (single-nucleotide polymorphism) genotyping array for radiata pine has been developed after several years of collaborative work between RPBC and Scion. It has already been used for parentage reconstruction and will be used operationally for GS (e.g. Grattapaglia & Resende, 2011) of seedlings in the nursery.

In validation studies, predictive abilities of tree performance using genotype information have been favourable, indicating the effectiveness of within-family selection of seedlings. The proposal is outlined in Figure 4. The CP orchard is producing ~10,000 seeds from selected parents to be sown in a nursery and grown to six-month-old seedlings. This material will include a proportion of somatic embryogenesis (SE) derived clones from the top parental crosses via green cones.

Needle samples are taken, and DNA extracted is and genotyped following the selection of 10%–15% of seedlings based on GeBVs and relatedness constraints. These are then entered into clonal test trials to be phenotyped and for re-training or validation of the GS model. Concurrently, a proportion of the top clonal test trial entries will be archived. There will still be a four to five-year time lag before these are reproductively mature, but as soon as this is reached pollen can be collected and crosses made.

Archiving selections into an orchard is key if the generation interval of the breeding population is to be reduced to the target of nine years (Figure 5a), which compares with a current average generation interval of 17 years (Figure 5b). To meet the nine-year target, interventions may be required in the breeding orchard, such as top grafting.

Various scenarios of resource allocation under GS using stochastic simulation are currently being tested to compare rates of genetic gain and inbreeding. This includes alternative ways in which seed orchards could be structured under GS to enhance deployment gain. Options for various new genotyping platforms are also being considered to reduce genotyping costs. Even though SNP array genotyping costs are still considered high, an economic analysis (Evison, 2019) indicated that while the internal rate of return was sensitive to genotyping costs, the profitability of using GS was higher than for conventional selection under several current assumptions.
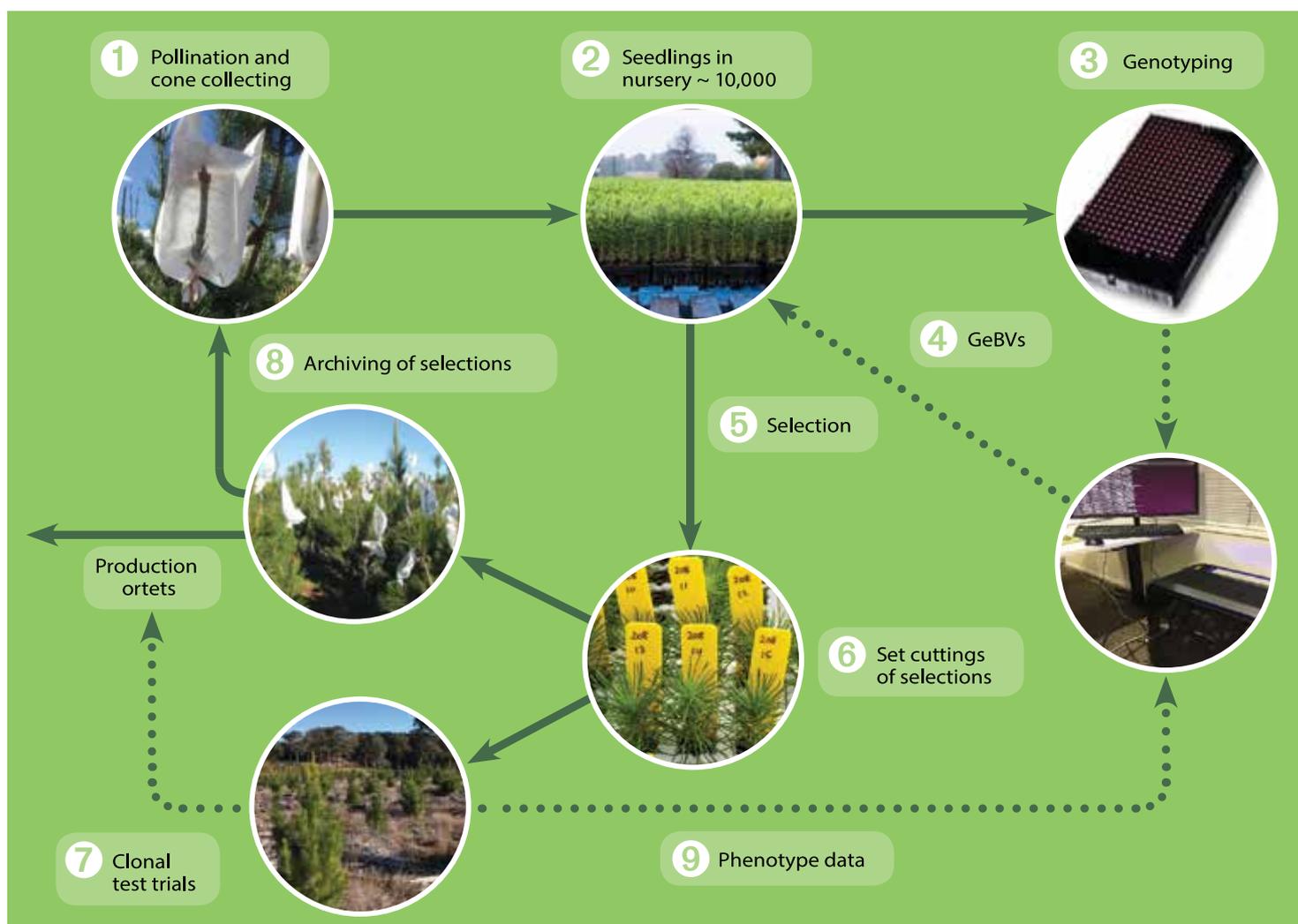

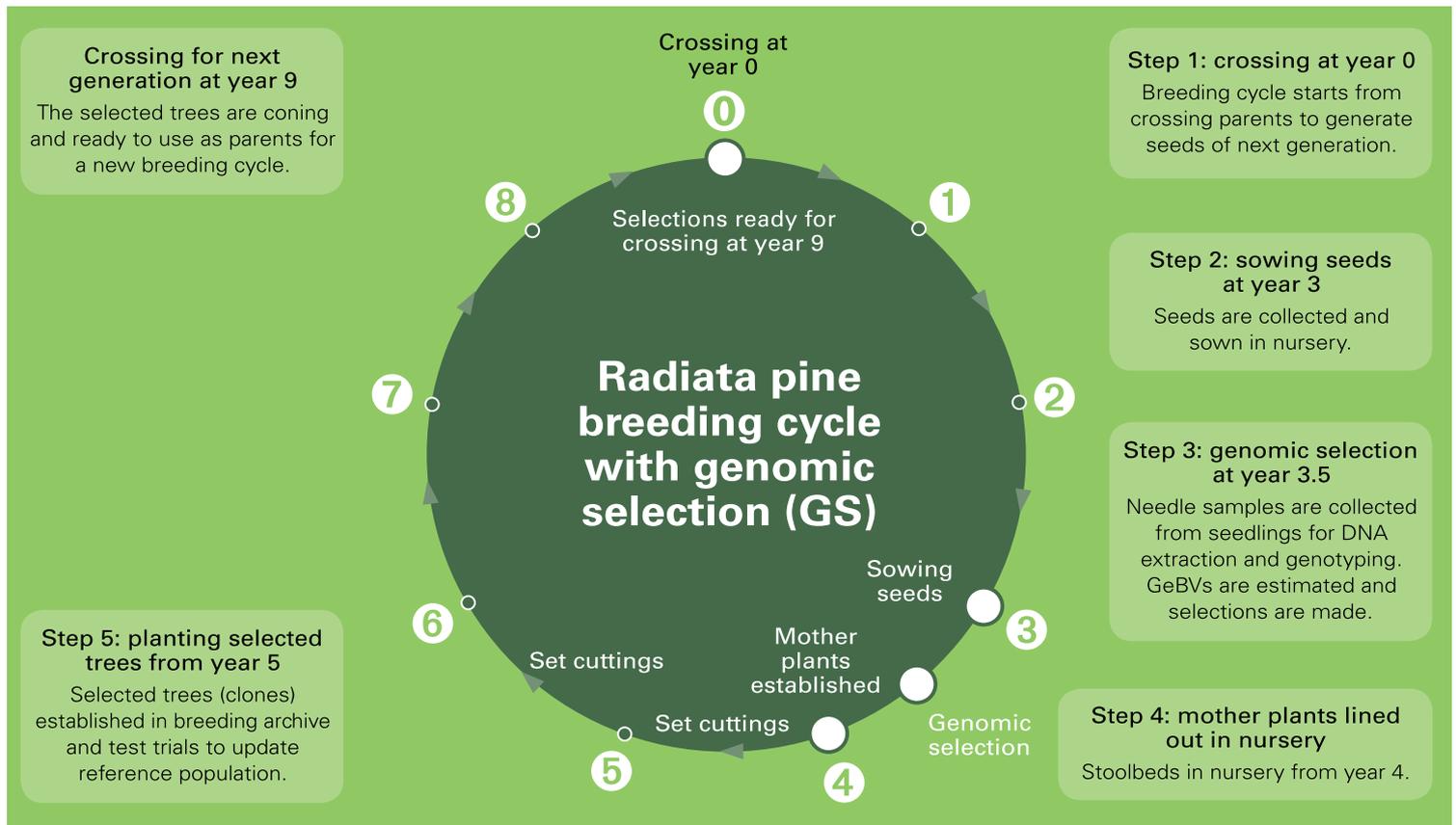Figure 4: A proposed breeding cycle under genomic selection

Figure 5a: Breeding cycle of nine years for radiata pine under genomic selection. Modified from Li, Y. & Dungey, H.S. 2018. PLOS ONE: doi.org/10.1371/journal.pone.0208232
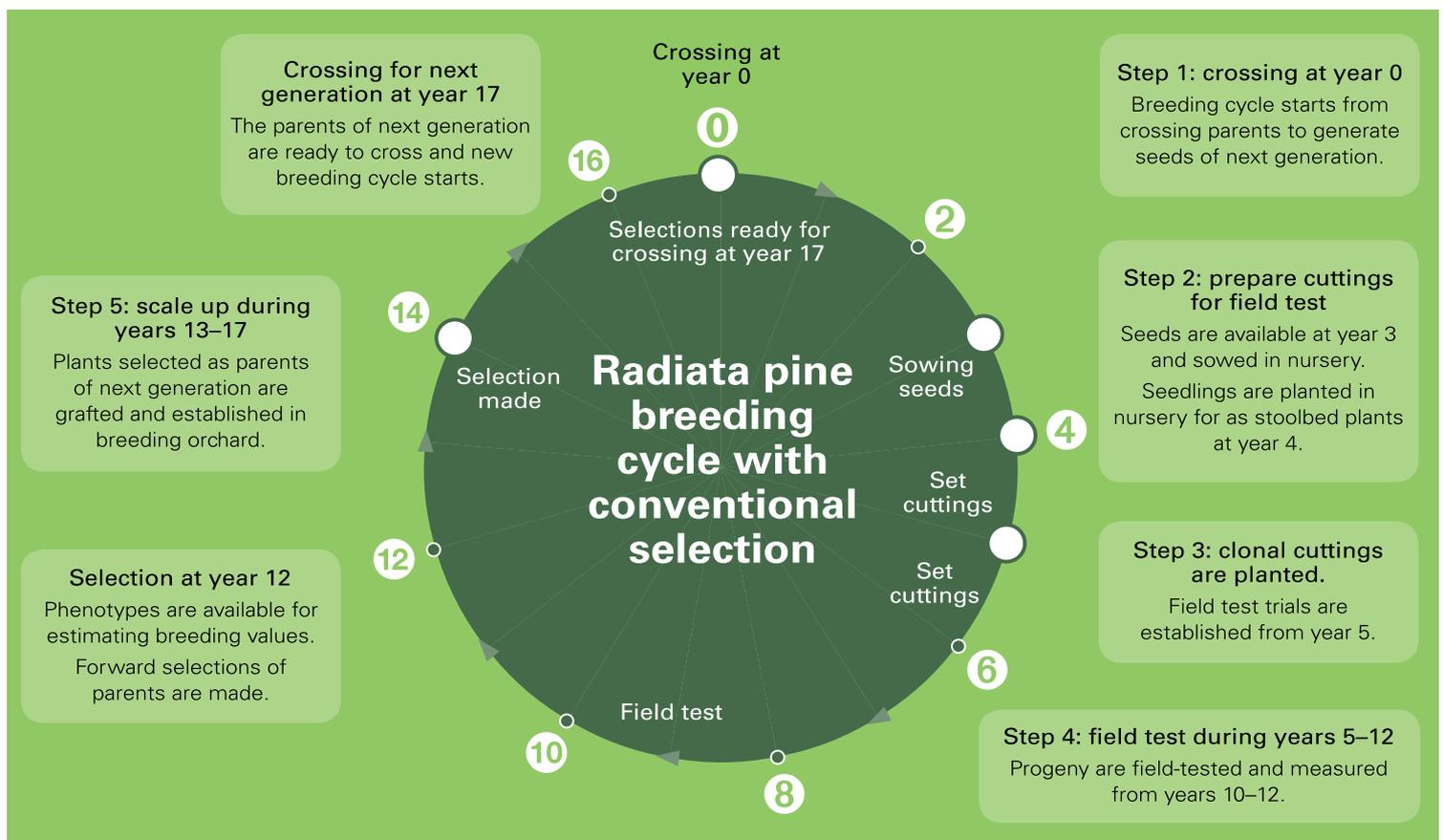

Figure 5b: Breeding cycle of 17 years for radiata pine under conventional selection. Modified from Li & Dungey (2018)

Genotype-by-environment interaction

The presence of qualitative genotype-by-environment interaction (GxE), where there is a re-ranking of genotype performance over different environments, can compromise genetic gain. Understanding the magnitude and type of G×E effects for traits helps to re-evaluate breeding strategies and improve selection efficiencies, as well as assisting in optimal deployment.

Carson (1991) found evidence of GxE effects for growth traits, but the magnitude was relatively small, and it was concluded that there was no justification in regionalising the breeding programme given the associated extra cost. In this study, testing on a small number of well-chosen sites accounted for over 90% of the predicted gain. Johnson et al. (1990) came to similar conclusions about regionalisation.

Although these studies were possibly limited in their scale, there is no convincing research to date to contradict these findings, and the RPBC multi-environment testing regime and selection strategy is built on this premise (i.e. the breeding population is non-regionalised and test trials are sited over a relatively small number (~5–8) of well-chosen and representative locations to ensure as clear a genetic signal as possible from the environmental noise and to obtain 'average' EBVs for all traits).

It is generally acknowledged, however, that there is a level of crossover GxE present for some traits, with growth characteristics being the most interactive. Elevation, precipitation, snow, temperature, underlying geology and prior land use have all been variously cited as important factors. A better understanding of this could be exploited at the deployment stage to improve productivity and rates of genetic gain in the production forest in addition to that achieved in the breeding population (e.g. better site matching of genotypes, particularly when deploying SE clones).

The opportunity for 'regionalised' breeding values for foresters is often discussed, but is not necessarily straightforward to implement, not least because 'regions' in New Zealand and Australia have been difficult to define. In any given arbitrary region, there can also be limited data to estimate breeding values with confidence, particularly if genetic connectedness is poor.

The approaches used by the RPBC previously have been analytical rather than descriptive in terms of environmental drivers, but there are opportunities to develop 'envirotypes' by grouping similar sites based on important climate and edaphic factors from principal component analysis or machine learning. Reaction norms can then be modelled to predict an individual's breeding value as a function of the envirotype covariate. This gives a curve for each genotype and predictions in both tested and untested environments. The response curves can be used to identify high-performing and stable genotypes (general purpose) or to obtain EBVs at particular envirotypes.

Deployment lag

The RPBC has limited control over the deployment population. There is therefore a potential lag of genetic gain during translation from the breeding population to the production forest where its value is realised. Seed producers must understandably trade-off seed production considerations with the turnover of orchard parents (i.e. the lower the average age of the seed orchard, the higher the expected genetic merit, but this younger age class structure may reduce potential seed yield). This is not helped by the slow multiplication rate of orchard selections (as grafted scions) for establishment in CP seed orchards and the time radiata pine takes to reach reproductive maturity.

Operational GS in the tree breeding programme may require a re-think of the structure of seed orchards to maximise deployment gain. Breeding cycles (and genetic gain) in the breeding population will speed up under GS, but deployment gain will increasingly fall behind if turnover rate in seed orchards does not respond. For example, the rate of deployment gain could possibly be increased if there was a faster creation and turnover of smaller OP orchards based on GeBVs.

Various approaches are currently being tested using stochastic simulation of seed orchard composition. More informed decisions on selecting SE clones for production clone testing will also be made and this could, in turn, speed up deployment gains via clonal forestry (Carson et al., 2015). RPBC is currently targeting the entry of 5%–10% of the top parental crosses annually (as an 'open nucleus') into the SE pipeline and, alongside GS, aims to speed up deployment of improved germplasm in both New Zealand and Australia. A current industry-led research initiative overseen by the NZ Forest Growers Research aims to scale up the production of somatic clones in radiata pine.

Closing the genotype-phenotype gap

Genotyping technologies have made much progress in the last few years, and even though their transfer and application to breeding programmes has rarely matched the early promises, routine operational implementation in tree breeding programmes is now becoming a reality. Good phenotypic data is important for accurate breeding value estimation and the successful delivery of genomic technologies, but phenotyping in plant breeding has not kept up with advances in high-throughput genotyping.

Further, the lack of opportunities to feasibly measure standing trees routinely in test trials for a wider range of traits (such as height, resin pockets, spiral grain, browsing damage, timber strength, dimensional stability, fibre content, diseases and stress tolerance) at a scale required for genetic selection has been a constraint to the development of breeding objectives, targeted end-uses and GS involving new or novel traits. This phenotyping bottleneck can hinder the ability of a programme to change tack quickly if the need arises.

Tree breeders are still, for the most part, measuring the same limited number of traits using the same methods that were being used decades ago, including an over-reliance on subjective scoring for several form and disease characteristics. The collection of trial data is time-consuming and is one of the most costly operations in a tree breeding programme. New high-throughput phenotyping technologies with proximal and remote sensing using ground-based and unmanned aerial vehicle (UAV) approaches to measure growth, form, disease and physiological traits are showing promise in tree breeding.

The expectation is that these technologies, along with machine learning approaches to handle the vast amounts of data that will be collected on standing trees in single tree plots, large block trials and plantations, will develop rapidly for the scaling-up and regular capture of data. This will be an important research focus for RPBC in the next few years.

Threats from pests and diseases

There is a requirement to build resilience into the RPBC breeding programme given the uncertainties faced with a changing climate and other concerns, such as biosecurity threats. These include *Dothistroma* variants not currently found in New Zealand and Australia, *Fusarium circinatum* (pine pitch canker), *Lecanosticta acicola* (brown spot needle blight), as well as potentially invasive insects *Thaumetopoea pityocampa* (pine processionary moth) and *Lymantria dispar dispar* (European gypsy moth).

RPBC germplasm is currently being screened for some of these pests and diseases in Europe to better understand the response. New screening methods are also required for red needle cast (*Phytophthora pluvialis*) and *Cyclaneusma* needle cast as field screening in breeding trials is unreliable. Despite these approaches to 'pre-emptive biosecurity', it is recognised that serious crop disease incursions in New Zealand in recent years have been largely caused by unforeseen agents (e.g. *Pseudomonas syringae* pv. *actinidiae* (psa) in kiwifruit and Liberibacter in *Solanaceae* crops).

Contingency and alternative species

There are opportunities to identify and develop potential radiata and other *Pinus* hybrids to build more resilience into the breeding programme. Unfortunately, there has been limited success in the hybridisation of *P. radiata* with other *Pinus* species to date, but *P. attenuata x P. radiata* is one of the few exceptions. Hybrid trials established in 1992 by NZFRI on 'semi-continental' sites have shown better growth, form and survival, largely attributed to better tolerance to snow load compared with radiata pine (Dungey et al., 2011; Paget, 2021).

RPBC is currently developing a breeding strategy for the *P. attenuata x P. radiata* hybrid. There is growing interest in establishing the hybrid at the margins of the radiata pine range where Douglas-fir has until recently been a preferred species on higher altitude sites. The hybrid is likely to contribute much less to wilding pine spread compared with Douglas-fir, which has had a detrimental environmental impact in some regions. The hybrid is considered as a contingency species and RPBC are currently reviewing opportunities to work with other potential contingency and alternative species, particularly radiata hybrids.
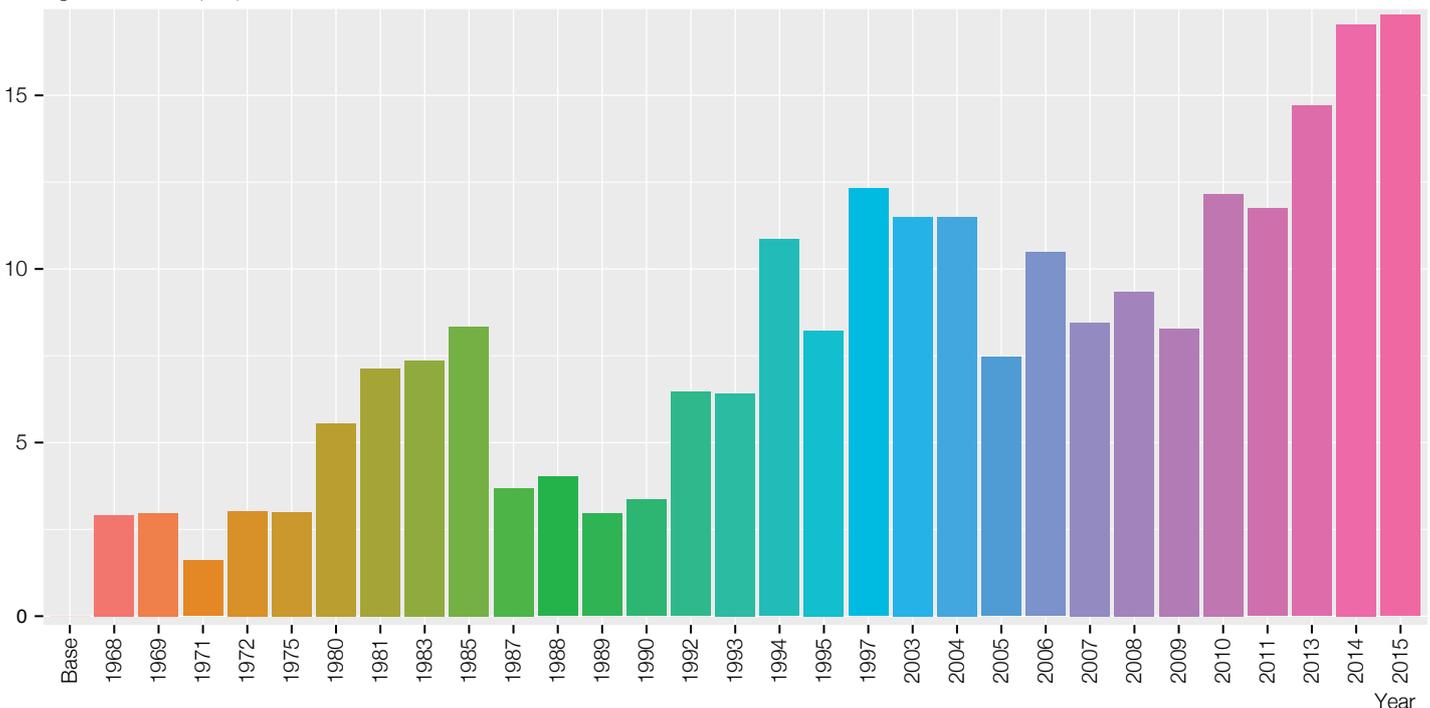
Average EBV – DBH (mm)

Figure 6: Trend in EBVs for diameter (mm) at breast height (DBH) in the RPBC breeding population

Proof of gain

Genetic trend in the breeding population

Improved tree form was quickly observed after the plus-tree selections of the earliest generations. With its low heritability, genetic gain in growth has been more difficult to demonstrate and wood properties did not become a focus until the 1990s. However, a positive genetic trend for DBH EBVs across years in the breeding population can be shown (Figure 6).

A trend in selection index ($NPV/ha) can also be illustrated. Figure 7 shows the so-called 2003/04 RPBC breeding series and progenitors. This breeding series, which can be traced back to the very early plus-tree selections described earlier, forms an important part of the current breeding population.

Realised gains in large block trials

Genetic trends demonstrated in the breeding population are from breeding trial data (i.e. trials made up of small, non-contiguous single tree plots). Measuring gains from large block trials made up of commercially available seedlots, clones and unimproved seedlots is the preferred approach used to quantify realised gain. It is more comparable to a deployment setting and likely to be more meaningful for foresters.

A study of realised gain in large block trials made up of RPBC germplasm by Kimberley et al. (2015) found that a unit increase in GF Plus seed ratings, which are related to EBVs, was associated with a 1.5% increase in volume growth rate. The magnitude of the increase, in absolute terms, was greater on more productive sites than less productive sites, but in percentage terms the increase varied little between sites or regions.

Conclusion

Breeding strategy in the RPBC programme is constantly evolving with a commitment to improving breeding efficiencies and delivering genetic gain to the New Zealand and Australian forestry sectors. Challenges such as a better understanding and exploitation of GxE effects and the routine use of new phenotyping technologies have yet to be resolved, but new opportunities (such as genomics) are now being implemented. Interested readers are also referred to Butcher (2015) for a previous, but recent, RPBC perspective.

Productivity gains from previous decades of the radiata pine breeding effort have been transferred to the production forest and the implementation of a genomic-led RPBC breeding strategy as an integral part of tree selection promises to deliver genetic gain more rapidly. Building resilience into the programme to face future market and climate challenges will require the RPBC to consider a greater range of traits, alternative species/hybrids, the development of new high-throughput measurement tools, and the implementation of new genomic applications.
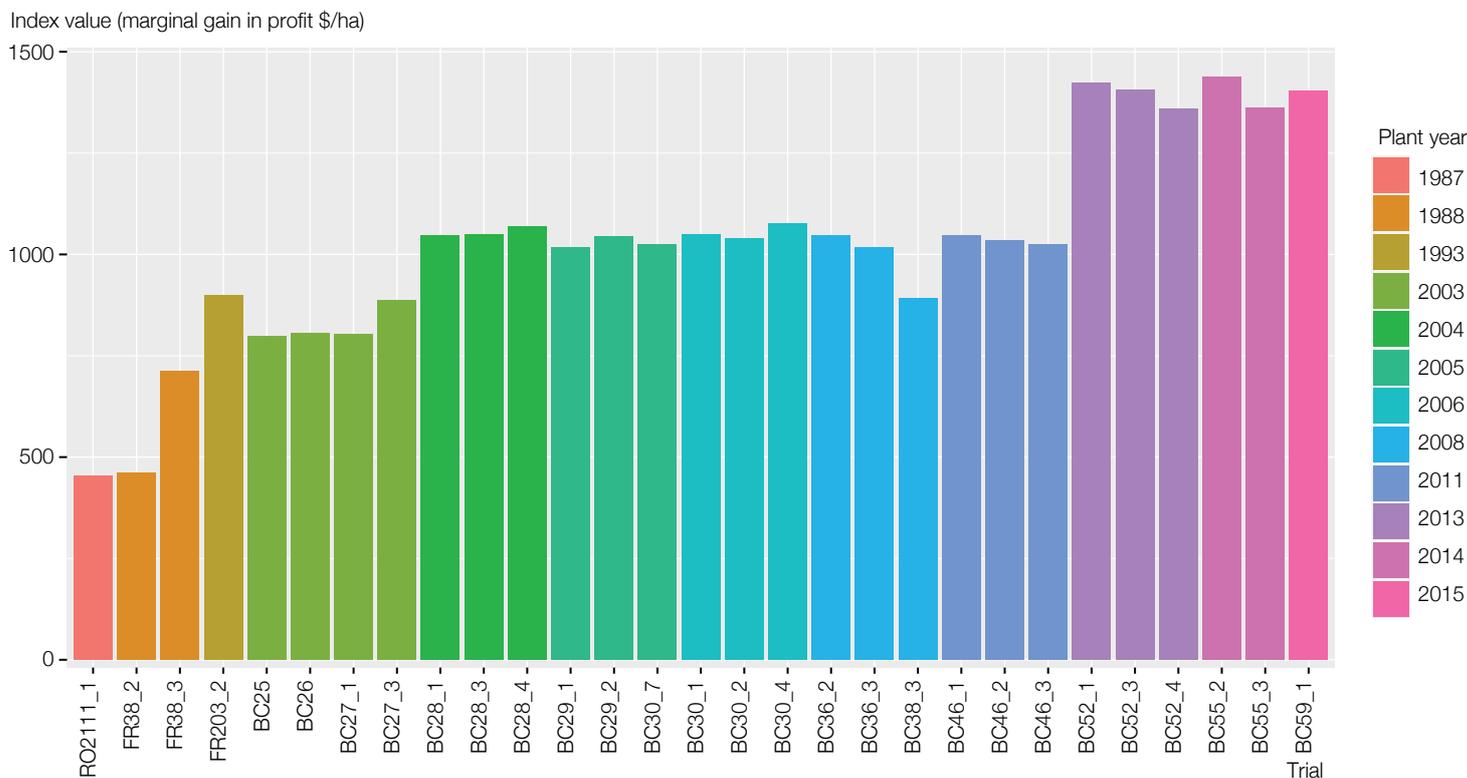
Acknowledgements

Figure 7: Trend in RPBC breeding index ($NPV/ha) for '2003/04' series trials grouped by establishment year

years of involvement in radiata pine improvement. David Evison (University of Canterbury School of Forestry) and Jaroslav Klápště (Scion) are also gratefully acknowledged. The shareholders of the RPBC are also thanked for their ongoing support of the breeding programme.

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Log segregation for a structural lumber mill based on stand location and log position within trees

Glen Murphy

Abstract

For the wood processing value chain to operate efficiently and profitably, processors need to obtain the wood raw material resource best suited to their needs. This may mean wood suppliers identifying and segregating stands and logs based on internal wood properties, as well as log external properties. A techno-economic model was developed that allowed calculation of mill-gate return-to-log (RTL) values ($/m³) based on log external characteristics and wood density. Stem descriptions from eight stands located in four wood supply regions around New Zealand were input to the model. Data from 8,271 logs were output from the model and segregated into groups based on stand location, small end diameter (SED) classes and position up the stem where the log was cut.

There were statistically significant differences in RTL due to stand location, SED and log position. For a given log SED class, RTL was shown to differ between stands and to decrease with height up the stem. These differences are due to differences in the wood density of the logs between stands and between positions in the stems. Individual log identification (log ID) may provide an opportunity for forest owners and wood processors to segregate logs based on wood property differences and to potentially share improvements in value recovery.

Introduction

The Forest Growers Research programme Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age commenced on 1 January 2019. The programme outlines a pathway for the New Zealand forest industry to develop innovative harvesting technologies in forestry automation and robotics that will address labour shortages, reduce forestry value chain costs, improve the economic viability of harvesting small forests, and enhance long-term sustainability through reducing environmental impact and making harvesting jobs safer for workers (Forest Growers Research, 2018).

One of the projects within the research programme is the development of an automated individual log ID tagging and tag reading system. Individual log ID has great potential for improving production efficiencies in the log value chain from stump to port or ex-mill gate. These systems can ensure that the right log product is allocated to the end product for which it is best suited, and they can help to control costs and maximise customer service. Tagging and tracking of logs is a common practice within export log supply chains, but it is little used within domestic log supply chains in New Zealand.

For the wood processing value chain to operate efficiently and profitably, processors need to obtain the wood raw material resource best suited to their needs (Murphy et al., 2010). This may mean identifying and segregating stands and logs based on internal wood properties, as well as log external properties (Manley, 2002).

A large European programme, called Indisputable Key, looked at developing tagging and tracking systems for forestry supply chains in Europe. It emphasised the importance of quantifying the benefits of such systems for wood processors and forest owners. The Indisputable Key programme demonstrated, for example, that timber drying times could be reduced by 4% if wood could be classified as either 'low' or 'high' density. It also demonstrated that segregating logs based on stand location could yield increases in lumber volume recovery, lumber grade recovery and sawmill productivity (Uusijarvi, 2010).

Historically, trees have been converted into logs and these are sorted based on external attributes such as diameter, length, straightness, branch size and the presence of obvious defects such as end checks, decay and resin bleeding. While these attributes affect the yields of products that can be obtained by a mill, they have little impact on end product performance, which is mostly driven by the internal wood properties of logs.

Processing operations differ in their wood raw material requirements, depending on the product that they are making (Moore & Cown, 2015). Mills making structural products (such as dimension lumber, glue-laminated lumber and laminated veneer lumber) generally require logs that will give high yields of products with acceptable stiffness and low warp (Perstorper et al., 1995). Wood density has been shown to affect stiffness, twist (Cown et al., 2004) and structural lumber grade recoveries (Wood Quality Initiative Ltd, unpublished data).

Over 95% of the plantation forest volume harvested in New Zealand is cut into logs using mechanised processing machines (Visser & Obi, 2020). Most of the mechanised log processors use the Standard for Forest machine Data and communication (StanForD) protocol for recording log data (Skogforsk, 2007). Among the many attributes that can be linked to each log are the stand from which the log was harvested, its grade, its small and large end diameters, its length and its location up the stem. An individual log ID number can also be allocated to the log and stored in the StanForD files.

This paper explores the effect of one internal wood property (density) on the variation in mill-gate return-to-log (RTL) values arising from differences between stands and positions within stems. If there

are significant differences in RTL values, there may be benefits for tagging individual logs in domestic supply chains, as well as in export supply chains.

Methods and materials

Model description

The techno-economic model SEGMOD, described by Murphy and Moore (2018), was used with trivial modifications to derive mill-gate RTL values based on external and internal log and wood properties for a representative mill cutting structural lumber.

RTL value is not market price, which will depend upon many things, including the general supply and demand for logs with particular attributes and the current financial position of individual buyers (Kininmonth, 1987). RTL values are indicators, however, of the potential worth of logs to buyers. Mill-gate RTL values, expressed on a per cubic metre basis, were calculated for each log using the following equation:

Mill-gate RTL ($/m³) = (Total Value of Products – Processing Costs)/Log Volume – Mill Yard Costs

where:

*Total Value of Products ($) = (Lumber Value + Chip Value + Hog Fuel Value) * (1-Margin for Profit)*

Lumber Value ($) = Volume Conversion Factor* $\sum_{i=1}^{n}$ LumberGrade%$_i$*LumberPrice$_i$

*Chip Value ($) = (1- Volume Conversion Factor) * Chip% * Chip Price*

*Hog Fuel Value ($) = (1- Volume Conversion Factor) * Hog% * Hog Fuel Price*

Volume Conversion Factor (ratio) = Proportion of log volume converted to lumber

LumberGrade%$_i$ = % volume in i^{th} lumber grade

LumberPrice$_i$ ($/m³) = price of ith lumber grade

Chip% = % of wood waste suitable for chips

Hog% = % of wood waste suitable for hog fuel

Volume conversion factors (% of log volume converted to lumber) for the structural grade mill were based on radiata pine sawing studies carried out by the New Zealand Forest Research Institute in the 1980s (Cown et al., 1987). Small end diameter (SED), sweep and taper were the key parameters in the deterministic equation used to calculate the volume conversion factor. Volume conversion factors used in our analyses also included a timber-loss factor (7%). Chip and hog percentages were assumed to be equivalent to 75% and 25% of the non-lumber volume, respectively. The margin for profit was assumed to be 7.5%.

Radiata pine structural lumber grade recoveries were based on models fitted to data from mill studies undertaken using logs from radiata pine stands in the Central North Island of New Zealand (Wood Quality

Initiative Ltd, unpublished data). Wood density is the key driver of grade recovery in these deterministic models, which predict the percentage of recovered volume in each of the New Zealand structural timber grades (Standards New Zealand, 1993). Other non-dimensional log quality attributes are not drivers in these models.

The following prices used in the model are averages from four regional price and cost datasets assembled in 2017:

- Lumber prices: MSG12 + $635/m³, MSG10 $605/m³, MSG8 $555/m³, MSG6 $395/m³ and MSG<6 $290/m³

- Chip price: $52/m³ solid wood equivalent

- Hog fuel price: $11/m³ solid wood equivalent

- Log processing costs: $140 per m³ of output

- Mill yard costs: $2.50 per m³ of input.

These data may have changed slightly since then but are sufficient for determining relative differences in mill-gate RTL values, if not absolute differences.

Log data

Log data were derived from eight stands in four different regions within New Zealand (Figure 1). Table 1 summarises basic information for the eight stands.
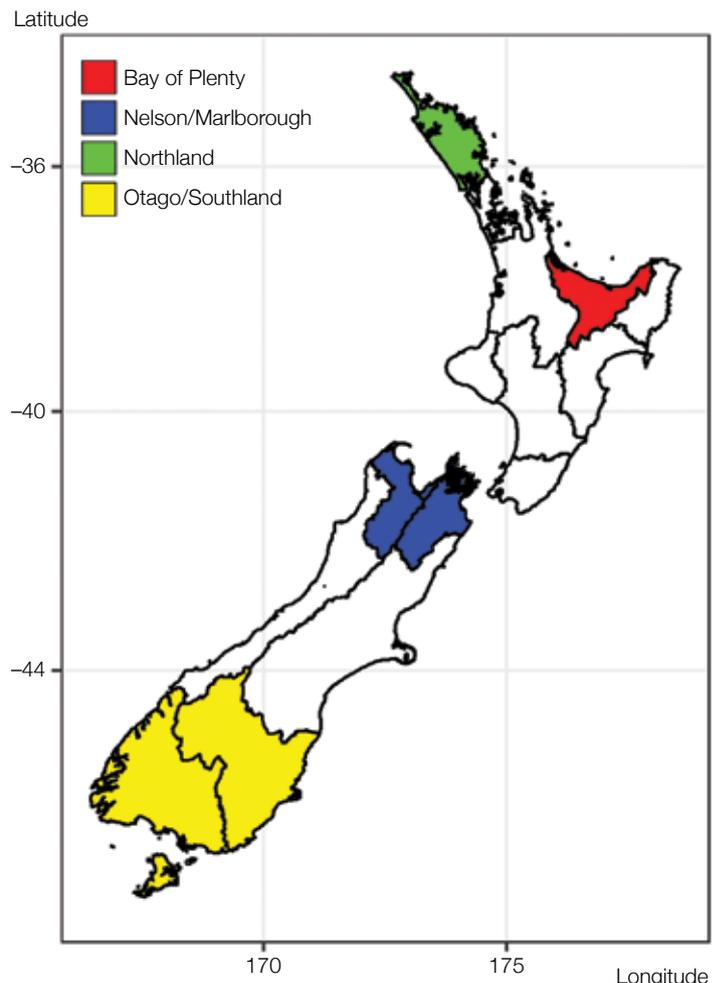

Figure 1: Location of the four study regions in NZ. Source: Murphy & Moore, 2018

Table 1: Basic stand data for eight stands located in four regions

	Region							
	Northland		Bay of Plenty		Nelson/Marlborough		Otago/Southland	
Stand ID	I	II	III	IV	V	VI	VII	VIII
Age (years)	24	24	28	25	25	24	29	27
Stand density (stems/ha)	434	338	324	504	493	502	276	299
Merchantable tree size (m³)	1.65	1.77	2.08	1.48	1.71	1.20	2.08	1.94
Breast height outer-wood density (kg/m³)	466	442	421	410	431	420	404	395

Detailed stem descriptions from standard pre-harvest inventory assessments were provided by forest owners for two representative radiata pine stands in each of the four regions. Breast height outer-wood density information (mean and standard deviation), if available, were provided by the forest owners. Where wood density information was not available, it was predicted from national models (Palmer et al., 2013; Kimberley et al., 2015) based on stand location and age (e.g. see Figure 2).

Wood density values measured (or predicted) at breast height were stochastically allocated to individual trees within each stand based on the means and standard deviations. These were then extrapolated to other

Figure 2: Spatial variation in predicted *Pinus radiata* outer wood density across NZ for 20-year-old trees. Source: Palmer et al., 2011

heights in the tree stems using non-linear functions (see Equation (3) and Figure 5 in Kimberley et al., 2015).

The stem descriptions were converted to a format that could be used in the techno-economic model. These descriptions included: (a) stem length after breakage; (b) under-bark stem diameters; and (c) wood density. External and internal properties were described in decimetre increments up the stem. Secondary leaders from multi-leader stems were not included in the analyses.

Each stem was bucked into 5.2 m long logs and the average wood density calculated for each log. Logs with an SED less than 150 mm under-bark were excluded from further analyses. Up to seven logs were cut from each stem. Log positions were labelled from 1 up to 7, with log position 1 being at the base of the tree. It was assumed that there was minimal stem curvature in all logs cut.

RTL values were calculated for each log using the techno-economic model. These were sorted into groups by forest stand (StandID), log position and SED class. SED Classes A to I were in bands of 50 mm (e.g. Class A 150–199 mm, Class B 200–249 mm etc to Class I 550–599 mm). In total, 8,271 logs were included in the log dataset.

Statistical analyses

All analyses were undertaken using Statgraphics Plus 5.1 (StatPoint Technologies Inc, VA). A multi-factor analysis of variance (ANOVA) was carried out with RTL value being the dependent variable and StandID, log position and SED class being the factors. Factors were deemed to be statistically significant if the p-values were less than 0.05.

Post-hoc multiple comparisons of RTL values were carried out between sub-groups of log data using Tukey's honestly significant difference (HSD) multiple range tests. Comparisons were deemed to be statistically significantly different if they exceeded tabular values at the alpha = 0.05 level.

Results

Multi-factor ANOVA

Log densities ranged between 310–487 kg/m³, with an average of 378 kg/m³. Log SEDs ranged between 150–587 mm, with an average of 289 mm. RTL values ranged between \$81.91–\$222.84/m³, with an average of \$149.59/m³.
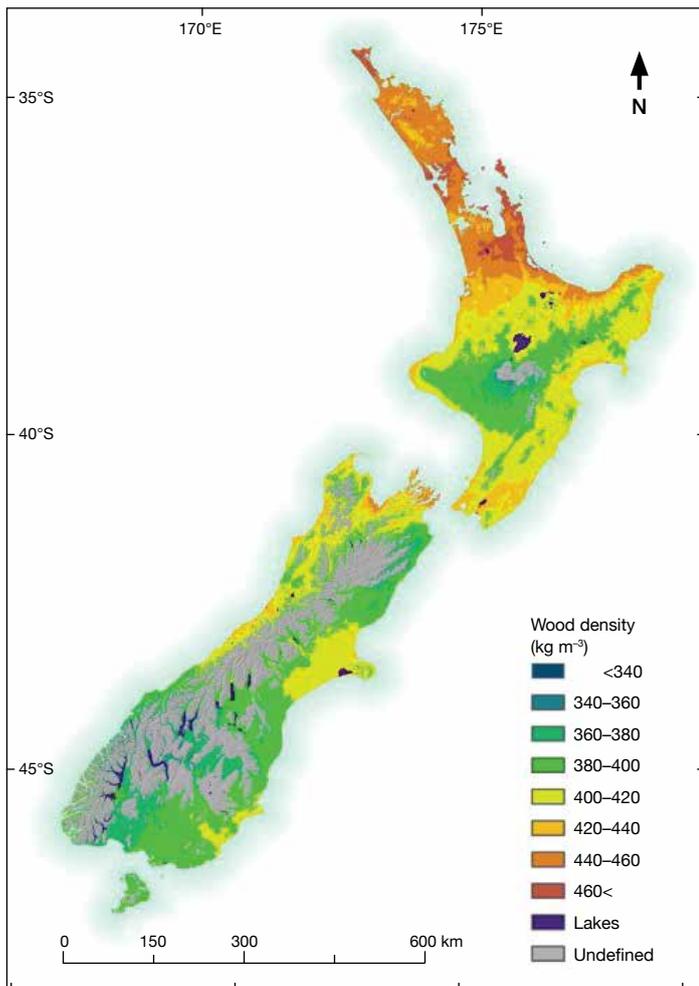
Table 2: Multi-factor analysis of variance for mill-gate RTL value – Type III sums of squares

Source	Sum of squares	Df	Mean square	F-ratio	P-value
Main effects					
A: StandID	1.40E6	7	200756	1385	0.0000
B: LogPos	3.36E4	6	55957	386	0.0000
C: SEDClass	1.18E6	8	147144	1015	0.0000
Residual	1.20E6	8249	145		
Total corrected	5.62E6	8270			
Note: All F-ratios are based on the residual mean square error.					

The multi-factor ANOVA showed that there were statistically significant differences in RTL values between stands, between log positions within a stem and between log SED classes (Table 2).

RTL values decreased non-linearly with height in the tree (Figure 3). Note that the HSD intervals are wide for log positions 6 and 7 (equivalent to 26–36 m up the stem) since so few logs were included in the data from these positions.

RTL values tended to decrease the further south in the country that the stands were located (Figure 3). The two stands with the highest mean RTL values were in Northland and the two stands with the lowest mean RTL values were in Southland/Otago. The trend closely mirrors the trend in wood density, with density tending to decrease with latitude.

RTL values increased non-linearly with SED class (Figure 3). Not surprisingly, larger logs had higher volume conversion factors, which yielded higher RTL values. Note that the HSD intervals are wide for SED Class I (SEDs from 550–599 mm) since there were so few logs of this class included in the study.

Comparisons of mean RTL values grouped by SED class

To facilitate understanding of the effects of stands and log positions within stems on RTL values, comment will initially focus on one SED Class C (250–299 mm), which contained 1,875 logs. The average SED of all logs included in the study was within this class (i.e. 289 mm). Comment will then be expanded to include other SED classes.

For the same log SED class, there was considerable overlap in the distributions of RTL values for different log positions in stems (as shown by Figure 4), even for a single stand. Similarly, for the same log SED class, there was considerable overlap in the distributions of RTL values between stands for the same log position. Figure 5 shows the distribution of RTL values for log position 3 for the two stands with the smallest and largest mean breast height outer wood densities. The distributions for the other six stands are not plotted, but the peaks of the distribution move to larger RTL values as breast height outer wood densities increase.

In Table 3, log positions within a stand (= row), with the same lowercase letter, are not significantly different from other log positions in the same row. Stands within a log position (= column), with the same uppercase letter, are not significantly different from other stands in the same column.
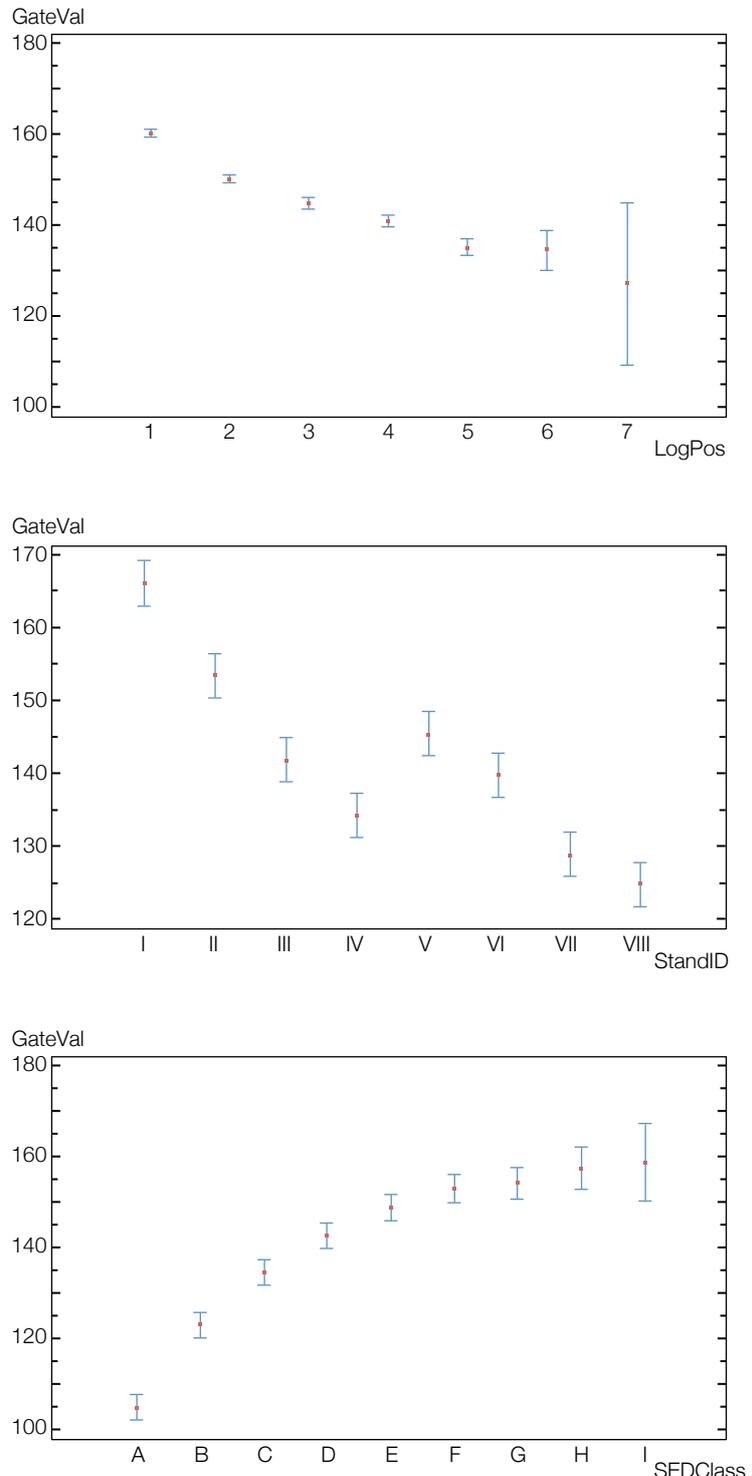
Means and 95% Tukey HSD intervals

Figure 3: Simple arithmetic means and Tukey's HSD intervals for mill-gate RTL values for three factors: log position up the tree; StandID; and SED class (classes are in 50 mm diameter groupings starting with group A being from 150–199 mm)

For all eight stands, mean RTL values, for SED Class C, decreased as the log position increased up the stem.

Table 3: Comparison of mean RTL values ($/m³) for SED Class C (250–299 mm) based on Tukey's HSD multiple range test (values have been rounded to the nearest $)

Stand	Log position 1	Log position 2	Log position 3	Log position 4
I	$180 a A	$170 b A	$159 c A	$156 c A
II	$166 a B	$158 a B	$146 b B	$142 b B
III	$155 a B, C	$141 b C, D	$134 b, c C	$134 b, c B, C
IV	$145 a D, E	$135 b D, E	$128 c D	$125 c D, E
V	$161 a B	$145 b C	$139 c C	$133 c B, C, D
VI	$150 a C, D	$139 b D	$136 b C	$131 b B, C, D, E
VII	$136 a E, F	$131 a, b F	$126 c D, E	$122 b, c C, D, E
VIII	$133 a F	$127 b E, F	$123 c E	$119 b, c E

For all stands, log position 1 had significantly higher mean RTL values than logs from positions 3 and 4, and for six of the eight stands log position 1 also had significantly higher mean RTL than for log position 2. Logs from positions 3 and 4 always belonged to the same grouping (i.e. there was no statistically significant difference between them). Mean RTL values for log position 2 always sat between RTL values for log positions 1 and 3, but for some stands there was no significant difference between higher or lower log positions.

This trend is similar to the trends for mean wood density for these logs which also decrease with position up the stem (Figure 6).

Comparisons of mean RTL values for given log positions showed that there were also significant differences between some stands (Table 3). Stands I and II (located in Northland) had significantly higher mean RTL values than Stands VII and VIII (located in Southland) for all log positions. Stands from the middle regions (Stands III, IV, V and VI) tended to fit into multiple groupings.

If comparisons are only made between logs from stands in the same region, mean RTL values were significantly different between Stands I and II for all log positions, between Stands III and IV for three of the four log positions, between Stands V and VI for two of

the four log positions, and between Stands VII and VIII for none of the four log positions evaluated.

Similar to SED Class C, there was a tendency in the other SED classes for mean RTL value to decrease with log position up the stem. Also, logs within the same diameter classes coming from positions high in the stem had lower, and statistically significant, mean RTL than logs coming from the base of the stem. Logs from intermediate positions were often not significantly different from logs from adjacent positions.
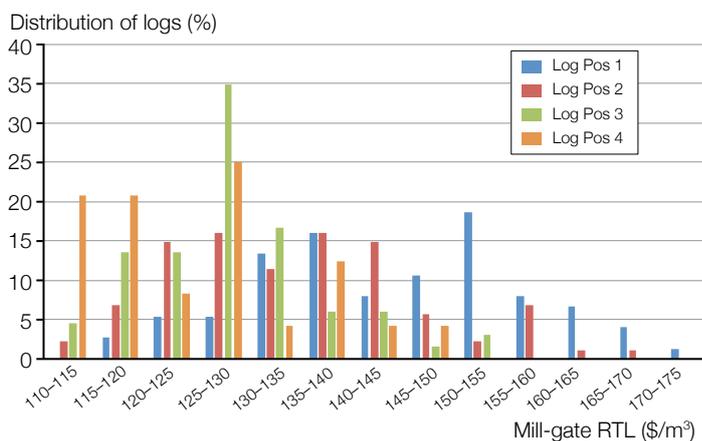

Figure 4: Distribution of logs by RTL values for four log positions and for Stand IV
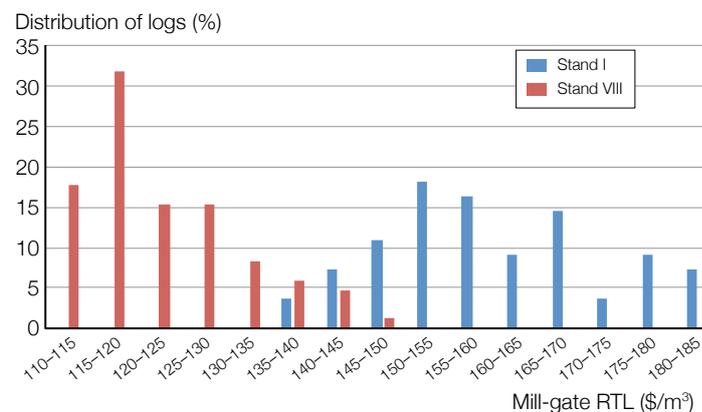

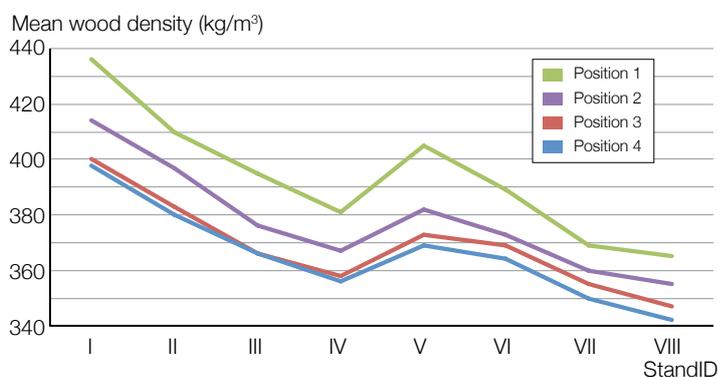Figure 5: Distribution of logs by RTL values for two stands and for log position 3

Figure 6: Mean wood density values of logs ranging in SEDs between 250–299 mm for eight stands at different log positions within stems

Relative changes in mean RTL values with log position

As noted above, the mean RTL values tended to decrease with height in the stem within each SED class. On average there were –7%, –11%, –13%, –14% and –18% differences between mean RTL values for log positions 2, 3, 4, 5 and 6, respectively, compared to log position 1 (Figure 7). It should be noted, however, that the relative size of the changes between log positions was neither constant, nor trending in a consistent manner, between SED classes.

Discussion and conclusions

RTL values were based on empirical models of volume conversion factors and structural grade conversion factors that had been developed by the New Zealand Forest Research Institute and WQI Ltd. Volume conversion factors are largely determined by log size (SED) and shape (taper, sweep); large logs having higher conversion factors than small logs. Grade conversion factors are mainly affected by wood properties (e.g. denser logs producing greater proportions of higher strength lumber).

Other studies have reported the impact of the variation in internal wood properties within stands and stems on RTL values. For example, RTL values of Douglas-fir logs in Oregon, destined primarily for lumber and veneer markets, have been shown to increase with increasing wood density (Acuna & Murphy, 2006, 2007) and increasing log stiffness (Amishev & Murphy, 2008, 2009) within stems and between stands.

In the analyses reported herein for radiata pine logs, there was a 174% difference in RTL value between the log with the smallest RTL value ($81.91/m³) and the log with the largest RTL value ($222.84/m³). Not unexpectedly, the RTL values were shown to decrease with height up the stem, to increase with increases in log size (= SED class) and to differ between stands.

Log markets pay a premium for log size (SED) in this country, but there is little evidence of a premium being paid for logs with superior internal wood properties within New Zealand or internationally (Murphy & Cown, 2015). The analyses showed, however, that logs within the same size class can have significantly different mean RTL values for wood processors, depending on which stands the logs come from (up to 40% difference) and where in the stem the logs come from (up to 18% difference). The differences are largely due to differences in wood properties.

It should also be noted that the density values for each log used in the analyses were not measured directly, but were first measured on a pre-harvest inventory sample of stems (or predicted) at breast height and then extrapolated to other stems within the stand and to other heights in the stems. It has been suggested by Scandinavian researchers that wood properties models similar to those used in our study
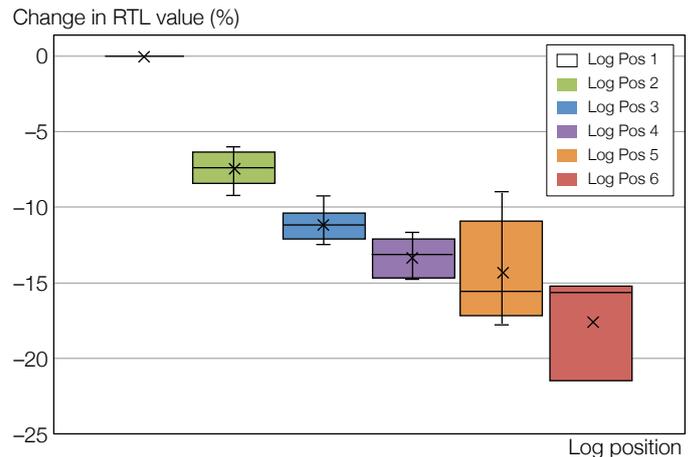

Figure 7: Box and whisker chart of change in mean RTL value, relative to log position 1, for all stands combined and for SED Classes A to F. The variation within a log position is due to differences between SED classes

could be used in bucking computers on harvesting machines to allocate logs to the most appropriate use (Wilhelmsson et al., 2002). Knowing the stand from which the logs came from and the position within the stem is an essential requirement for making the best use of these models. An individual log ID, attached at the time of processing stems into logs, would help to ensure that this information remains linked to the log.

Even if individual log ID's were not attached to each log, given that the logs in position 1 had a better RTL value than those in other positions across most SED classes, there could be value in marking these with the paint applicator on a processor head. While differentiating logs from the base of a stem from other log positions, this would not differentiate logs from other stands within the same SED class.

There are some limitations to this study. The results are based on volume conversion factors obtained from mill studies that are at least 20 years old and structural grade conversion factors that were developed from mill studies more than 10 years ago. The conversion factors may have improved with time with the implication that RTL values may be under-estimated. Also, the lumber prices and mill costs used in the analyses were based on averages that are at least five years old and may not relate to current market conditions or any specific mill. Nevertheless, the relative size of the differences in mean RTL values are not small and should be of some interest and relevance to forest owners and wood processors.

In conclusion, this paper has demonstrated that, for radiata pine logs of the same SED, there are differences in mean RTL due to differences in wood density arising from the position on the stem and the stand from which logs are cut. If the differences are considered by log buyers and sellers to be large enough to exploit, individual log ID tagging could provide an opportunity for forest owners and wood processors to segregate logs based on wood property differences and to potentially share improvements in value recovery.

Professional papers

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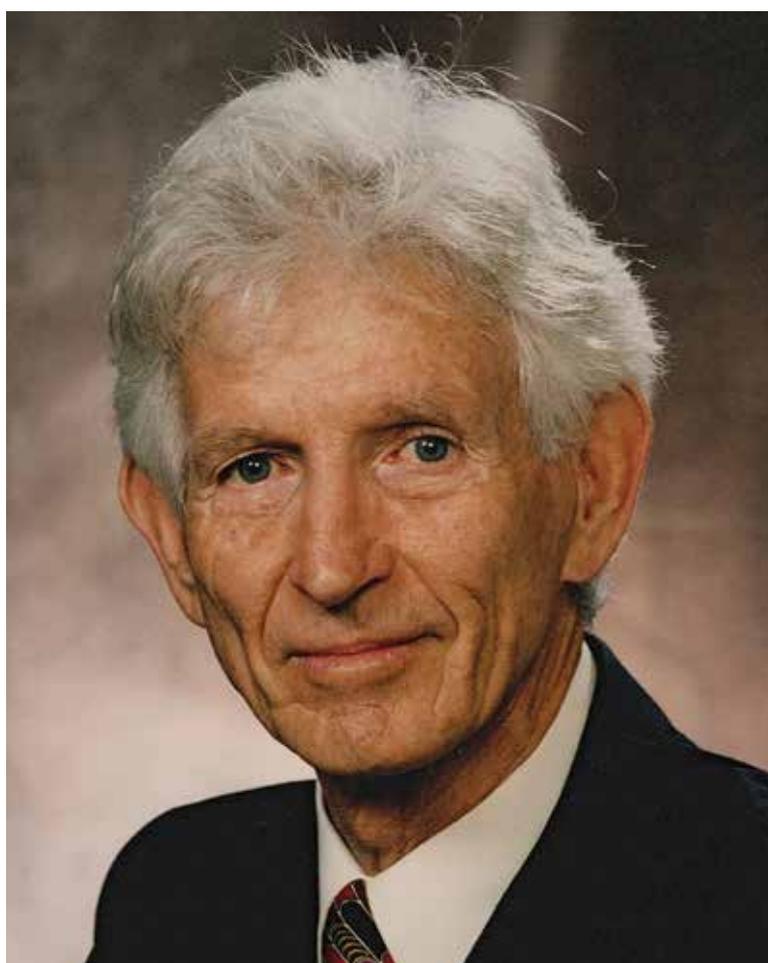
Geoffrey Bruton Sweet
14 March 1932 – 26 December 2020

Prepared by Ross Dickson

Professor Geoffrey Sweet was a leading figure in New Zealand forestry, actively advancing research, mentoring students from all over the world, and fostering a culture of collaboration and future thinking.

After graduating from King's College he attended Auckland University where he graduated with a B.Sc. majoring in Botany and Zoology; he was Senior Scholar in Zoology. Once employed at the New Zealand Forest Research Institute (FRI), Geoff was sent to Canberra to study for a Bachelor of Forestry degree at the Australian National University. The two years spent there not only allowed him to enjoy the Australian student

Geoffrey Bruton Sweet

life, but also travel widely and learn about the Australian forest environment. Geoff was a very successful student and graduated in 1958 as best all-round student from the course, earning the Schlich Medal.

Geoff was appointed to a role in the Forest Tree Genetics section at the FRI through the New Zealand Forest Service. The FRI encouraged him to seek research qualifications from a world-leading institution, and in 1963 he travelled to the UK to undertake his PhD

studies at University College of Wales, Aberystwyth under Professor P.F. Wareing, a leading Plant Physiologist of his time. Geoff worked on the physiology of growth rate in radiata pine and other conifer species, working long hours on his thesis amongst all the duties of bringing up a young family.

Returning to the FRI in Rotorua, Geoff's brief was to deliver the physiological research necessary to underpin the radiata pine breeding programme. His main research contribution at the FRI was in the area focused on the physiology of radiata pine pollination, and his detailed research proved crucial to the development of control pollinated seed orchards. He and his graduate students continued this research when he moved to the School of Forestry, with much of that work then being undertaken at the Amberley seed orchard. From 1978, he managed the FRI forest health programme, covering pathology and entomology, as well as tree breeding. Later this was expanded to include other areas of production forestry.

Geoff was also given special responsibility for computing services across the Forest Service. In his various management roles at the FRI he developed a

reputation for being a sympathetic leader who would listen to the concerns of staff, and take the advice of staff who had expert technical knowledge in areas beyond his own. It was in this spirit that he led the Institute and the Service into the adoption of computerised research systems in the early 1980s.

In 1979, he applied for and was awarded a D.Sc. from the University of Canterbury, a doctorate based on the quality of one's research output, in Geoff's case his research on the physiology related to radiata pine tree breeding. During his research life he published more than 80 papers and chapters of books, a number of them in partnership with overseas scientific researchers.

In 1985, Geoff and Margaret moved to Christchurch for him to take up the position of Professor of Forestry at the University of Canterbury. Here Geoff, known to his students as Prof, soon settled into the academic life of the university and enjoyed the stimulation that it provided. He continued and strengthened connections with the forest industry, the FRI other research institutes. Early in his tenure he oversaw the first major expansion of the building, expanding the size of the lecture rooms at the School and enhancing the administrative block. He proved to be an excellent leader for the School and will be remembered for his easy, outgoing personality.

At the School of Forestry, Prof and some of his graduate students undertook basic physiological studies of important native trees, including podocarps and beeches. An interesting conclusion by Prof and several of his postgraduate students from temperature growth studies was that our native trees have higher optimal temperatures than many temperate species, and this was presumably a hangover from the more sub-tropical conditions in the Miocene. Their findings seem to explain our lower timberlines and perhaps bode well for the adaptation of some of our major indigenous species to climate change.

Prof was a researcher and academic with the ability to bring science and commerce together, and to look at real life challenges through both a scientific and commercial lens. A rare skill in a research scientist. As an example, through his university role Prof forged a working relationship with Proseed NZ Ltd, a small government-owned company producing genetically improved radiata pine seed for the industry at a seed orchard at Amberley, North Canterbury. This relationship led to the establishment of an industry consortium known as the NZ Seed Orchard Research Group comprising New Zealand forestry corporates at that time. Prof had achieved a long sought-after collaboration for the industry, and before long he had four postgraduates working on radiata pine seed production. It was through this work, in part, that the industry was able to effectively set up large-scale industrial seed orchards across New Zealand to produce genetically improved seed for future plantation establishment, the benefits of which we are still seeing today.

Both Prof and Margaret took a genuine interest in each of us as postgraduates. We were always welcomed into their family home for celebrations and social catch-ups. Every year, they maintained an Easter tradition for the Forestry School's overseas students, organising an annual visit to the West Coast forests based at the School's Field Station at HariHari. As mentioned, Prof had significant diversity within his postgraduate team, studying a whole range of forestry-related topics from social forestry right through to plant physiology. It was through the fostering of the postgraduates and their achievements that both Prof and Margaret made tremendous contributions to all parts of the world, and particularly developing countries where the graduates would develop new skills and knowledge at the School and take them back to their home countries.

Geoff was a very progressive force within the New Zealand forest industry and was also Editor of the *New Zealand Journal of Forestry* for five years. He shared a lifetime's passion for the outdoors and led his family and friends on many tramping routes through the mountain country of both the North and South Islands. He was a natural and everyone who tramped with him had great confidence in his calm good judgement – he was trusted.

After retirement, in Christchurch, Geoff and Margaret established a new outdoor tradition for 10 days each January, booking accommodation in one of the many mountain lodges along the backbone of the South Island high country to explore a local river valley with a group of friends.

Geoff died on 26 December 2020. At his funeral there were many tributes for Prof from former students at the University of Canterbury. Without exception, the students he supervised for their postgraduate work described him as kind and patient and a man who influenced so many lives professionally and personally to the point that the Prof became our friend.

Bare-root or containerised forestry future?

Sebastian Klinger

They often say 'nothing lasts forever', and it seems not even systems and technologies that have served New Zealand forestry well for over 100 years are immune to this fate. Bare-root technology has been the mainstay for the establishment of plantation forests in this country. At present less than 20% of radiata tree stocks are grown in containers, with an increasing trend towards containers. So why change now?

With similar growing conditions and species to parts of Australia, South Africa and countries in South America, New Zealand plantation forestry systems are often compared to them. These countries have all moved away from bare-root production and are almost exclusively, and very successfully, using containerised growing systems.

These trends have also become key topics for some New Zealand forestry nurseries who are contemplating containerised growing systems. The most cited reasons to implement containerised growing systems are the reduced production period in the nurseries or an increased use of cuttings. However, labour shortages, skills, automation and the ability to extend the planting season using container-grown trees seem to be the decisive drivers today to move away from bare-root technology. Also, mechanised planting, which is of growing interest for some companies, requires containerised plants.

Nursery managers expect labour costs for lifting bare-root seedlings to increase in the coming years due to higher labour demand. Automation and ergonomics within the workplace are also considered, especially when labour shortages arise. Containerisation can automate a lot of these manual processes and provide more pleasant working conditions in sheds and at elevated propagation tables compared to crouching in the bare-root beds in the weather.

An extended planting season (e.g. eight months/year) offers greater employment certainty to nursery and planting contractors, and thus more continuity in the workforce, a problem that has plagued the industry for decades. Greater certainty means skills can be developed and retained in the industry rather than being transitory employment as it often is currently. As any forestry nursery manager will know, you can grow very good seedlings in the nursery, but as any forest manager will also know, if the planting or handling of those seedlings once they leave the nursery is poor then many of the gains can be lost, almost immediately. The benefits of increased flexibility around planting and dispatching times have certainly become more obvious after the COVID-19 lockdowns and the associated interruptions to nursery and forestry schedules, which could reoccur any time.

Undeniably, the initial capital costs to set up a containerised nursery are significant. Thus, establishment of these facilities requires a viable long-term economic decision, where cost-benefit analysis or modelling frameworks could help support decision-making. Perspectives of at least 10–15 years should be considered and investment in new infrastructure always requires a level of confidence in future markets. Some of New Zealand's big radiata producing nurseries have made the decision to grow container plants and for them it seems to be a profitable business case despite the high initial costs.

Predictions on the future always come with a level of uncertainty, but there are some global mega-trends which are expected to impact forestry and nurseries across New Zealand. Climate change will have an impact on seedling establishment. This concerns the time of planting and potentially drier planting sites and therefore the need for more flexibility around dispatch and planting.

New Zealand's Government has committed to carbon neutrality by 2050, confirmed by pledges to the Carbon Neutrality Coalition. It is one of just six countries in the world that have passed their carbon neutral targets into law. This creates a level of certainty on a long-term perspective that the ambitious afforestation goals by 2030 and 2050 will persist in the future and create a continuous demand for commercial forestry nursery plants.

Lastly, growing concern for environmentally-friendly practices, sustainability or hygiene in the nurseries (disease, run-off, fungicides, herbicides) will undoubtedly have some influence on certification, legislation and the social licence to operate in the future. In a fully containerised system, it is easier to implement non-chemical disease control and include integrated pest management alternatives. There is also increased opportunity to recapture, sterilise and reuse nutrients and water and prevent their escape into natural environments. The single use of growing mediums significantly reduces the likelihood for nurseries and seedlings to be vectors for soil-borne pathogens.

We will undoubtedly face increasing legislative and social pressure to lessen our impact on the environment. These factors will continue to drive improvements in our bare-root production systems, but will equally make containerisation a more and more attractive alternative.

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