Puruki Experimental Forest – half a century of forestry research

Loretta Garrett, Steve A. Wakelin, Stephen Pearce, Steve J. Wakelin and Tim Barnard

Abstract

Puruki Experimental Forest (PEF) is a second rotation *Pinus radiata* forest located in the Central North Island, New Zealand. It has been a showcase for leading forest science for over 50 years. PEF is part of the Purukohukohu paired land use catchment study installed in 1968 by the Department of Lands and Survey, the Ministry of Works Water and Soil Division, and the New Zealand Forest Research Institute of the New Zealand Forest Service. From the outset, PEF was visionary in ambition and scope and founded on interagency collaboration and support. Since establishment, PEF has provided valuable longitudinal data sets and the importance of these has increased over time. Data from PEF has been used to build and parameterise tools and models adopted by the forest sector and government agencies, particularly associated with carbon and nutrition, productivity models, genetics, disease and growth, and hydrological modelling and water quality assessments. PEF has underpinned much of our knowledge on how to design and sustainably manage a highly productive planted forest, whilst delivering wider forest benefits and ecosystem services to society. PEF is now nearing the end of its second rotation. The next phase offers a new opportunity to extend the legacy of PEF by undertaking ambitious, ecosystem-level research for the benefit of New Zealand.

The story of Purukohukohu Basin and PEF

In 1968, the Department of Lands and Survey, the Ministry of Works Water and Soil Division, and the New Zealand Forest Research Institute (NZFRI) of the New Zealand Forest Service established a significant research programme in the Purukohukohu Basin in the Paeroa Ranges of the Central North Island. The site was established under the umbrella of the International Hydrological Decade (1965–1974), a United Nations Educational, Scientific and Cultural Organisation (UNESCO) initiative to address a global decline in freshwater resources (Nace, 1964). This collaboration led to the design and implementation of an ambitious long-term research programme that sought to understand the effects of land use change on local hydrology and volcanic soils (Beets & Brownlie, 1987; Tustin, 1987).

The Purukohukohu Basin included paired catchments comprising native forest, pasture and pine forest planted into pasture – the Puruki Experimental Forest (PEF) catchment. Each catchment was similar for slope, aspect, soils, area and climate. Native forest had been removed from PEF and paired pasture catchments in the 1920s and the land had reverted to scrub. In 1957, the pasture was restored and improved with the application of super phosphates. This investment of fertiliser was to play a significant part in the research history of the site.

The interest of the NZFRI (now Scion) focused on productivity and dry matter production in the planted pine catchment. Today, the site is managed by Scion under lease from Pāmu (Landcorp) Farms. The original research agenda can be considered visionary in ambition and scope (Tustin, 1987). Fifty years on, PEF has delivered longitudinal data sets that have grown increasingly important over time and remain very relevant to the challenges we face today. The value of PEF goes well beyond the forestry sector to others actively engaged in sustainable land management:

> *'The commendable foresight of those involved in the Puruki research site is proving invaluable to those involved in forestry, agriculture and conservation alike. Having almost 50 years of scientific data measuring the interaction of forestry and agriculture on our waterways as well as nitrogen leaching and carbon sequestration is arguably more relevant today than they were when the Puruki trial was established. Pāmu are proud to be involved and remain committed to our role in continuing the legacy of Puruki.'*
>
> Andrew Sliper, General Manager (Pers comm)

PEF site and its management history

PEF lies on pumice soil with underlying ignimbrite and is typical of much of the Central North Island (Figure 1). In 1968, the three paired land use catchments were established, of which PEF was a total of 34.4 ha (Beets & Brownlie, 1987). The original pasture was restored after significant scrub encroachment and managed as a dry stock pastoral farm. In 1973, PEF was aerially sprayed to control weeds and planted with *Pinus radiata* 'GF7' (Growth and Form 7; GF rating scale) seedlot at 2,200 stems/ha (SPH).

PEF itself is made up of three sub-catchments and these delimited a thinning treatment in the first rotation imposed over the trial, with the sub-catchments 'tahi, rua and toru' stocked to final crop stocking of 550, 180 and 60 SPH, respectively (Beets & Oliver, 2007). The site received regular spraying with copper through the rotation to control dothistroma needle blight, a foliar disease caused by the pathogen *Dothistroma septosporum*.

During the first rotation research focused on forest water use, stream water chemistry, stand volume growth, biomass and nutrient uptake and cycling, forest floor accumulation, leaf area, needle retention, foliar disease, foliar nutrient status and soil chemistry. In 1976, a meteorological station tower was erected to collect climate data (Beets & Brownlie, 1987). The first rotation was harvested in 1997 aged 24 years. Two sub-catchments (180 and 550 SPH) were harvested with ground-based operations and the third (60 SPH) using a hauler system (Oliver et al., 2004).

The second rotation forest was planted soon after logging the first rotation. The second rotation PEF was established with a focus on: (1) genetic heritability of upper mid-crown yellowing (UMCY – an expression of tree magnesium deficiency (Beets & Jokela, 1994)); (2) productivity on low and high solar radiation aspects; (3) productivity between improved genotypes; (4) a later focus on the use of LiDAR to monitor forest carbon stocks; and (5) improvement of allometrics for calculating carbon stocks.

A single post-planting herbicide spot-spraying operation was used to control weeds. The experimental trials (12.5 ha) were established with a variety of *P. radiata* stock and stocking rates, medium and high pruned, one trial thinned and the rest of the trials were un-thinned (Beets et al., 2011b). The remainder of PEF (21.9 ha) was planted at 500 SPH using a mix of genotypes, medium and high pruned (350 SPH) and left un-thinned. The site received two copper sprays at tree age seven and nine years old.

PEF – a legacy of science impact

PEF has been an experimental forest since 1973 and is a unique resource for ecosystem-level research within New Zealand. Over many decades, PEF has deepened our understanding of watershed-level hydrology as well as forest health and productivity. This makes PEF a rare and valuable resource for this country, delivering far more than its original mandate when established under the United Nations Decade of Hydrology.

Also, data from PEF has been invaluable in the development and parameterisation of carbon and nutritional models for New Zealand's planted forests. It has provided new knowledge about the role and interaction of genetics, nutrition and growth, and forest productivity, nutrient flow, carbon balances, hydrological cycles and water quality. All of this has been made possible through visionary leadership that recognised the need for long-term forestry research in New Zealand, supported by continued investment into the maintenance of trials and ongoing data collection.

As we face an uncertain future in a changing climate, the demand for more experimental forests across various ecological zones throughout New Zealand is increasing. To achieve this, collaboration and an intentional move toward partnership and long-term environmental research investment is required. This is a need highlighted by the Parliamentary Commissioner for the Environment in a review of environmental research in New Zealand in 2020 (PCE, 2020).

Figure 1: Puruki Experimental Forest 1981

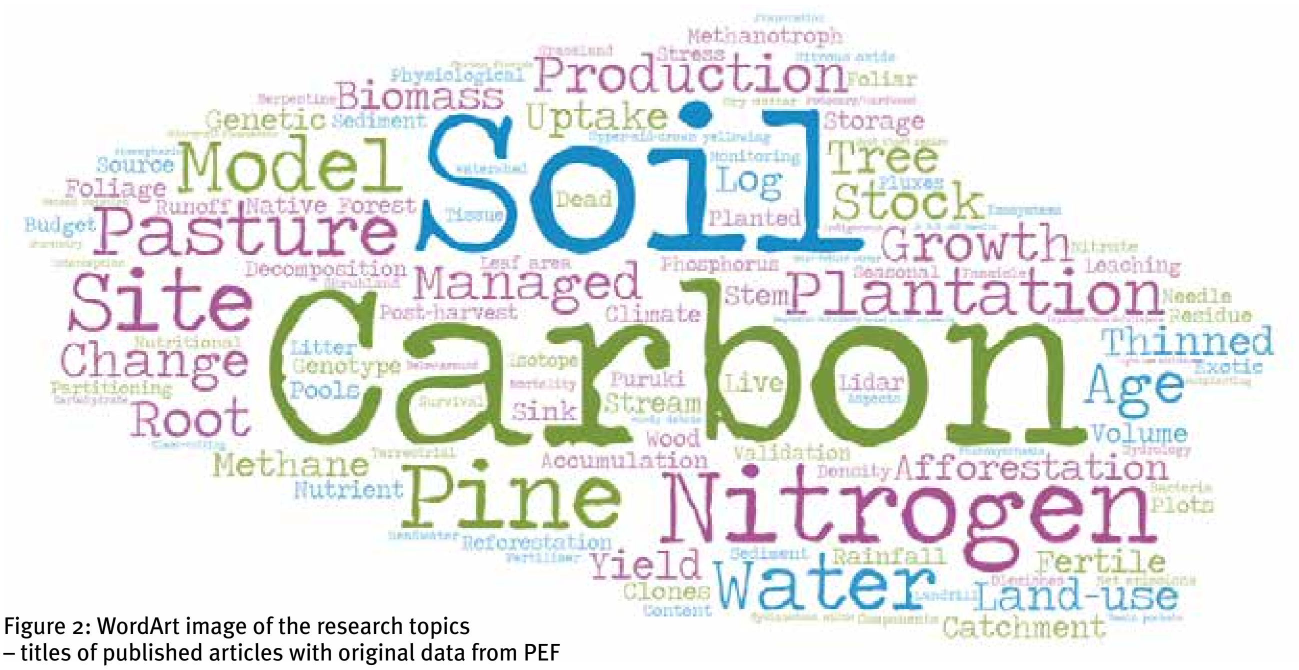

Figure 2: WordArt image of the research topics
– titles of published articles with original data from PEF

PEF remains an exemplar of what can be achieved with long-term forest-level trials. However, more than that, it is a signpost toward the need for a national series of secure and appropriately funded long-term forest ecosystem experiments in New Zealand. The following sections highlight some of the major impacts of the research undertaken at PEF.

A half century of research excellence

The impacts of this work have had a profound influence on forestry research and practice in New Zealand (Figure 2). By 2021, a total of 67 articles have been published using original data from PEF. If the forest were an author in its own right, PEF would have a Google Scholar h-index of 34/Scopus h-index of 26 (data as at March 2021).

Data to support nationally important forest models

PEF data has been critical to the development of nationally important tools that underpin carbon and nutrient predictions, including C_Change, Forest Carbon Predictor (FCP) and the Nutrient Balance Model (NuBalM) (Figure 3) (Beets et al., 1999; Beets et al., 2011a; Smaill et al., 2011). PEF provided the opportunity for the early application of LiDAR for remote sensing and monitoring of forest ecosystems (Beets et al., 2011b). LiDAR data from more than a decade ago helped demonstrate the importance of aspect and tree genetic data in improving stand productivity models (Beets et al., 2011b).

Data collected from the first rotation and early second rotation was comprehensive, especially the PEF time-series tree-biomass, and supported development of the C_Change model (Beets et al., 1999) which, in turn, underpins the FCP (Beets et al., 2011a) and the NuBalM models (Smaill et al., 2011). The flow-on impacts of data collected from PEF into New Zealand's models and tools should not be underestimated. For example, C_Change predicts annual carbon stocks in forest pools, including above-ground biomass, below-ground biomass, coarse woody debris and forest floor litter. C_Change, incorporated into Forecaster, is central to planted forest carbon assessments in New Zealand.

The C_Change model provides an integrated, consistent carbon estimation and projection system. This gives confidence in predictions used by agencies such as the Ministry for the Environment (MfE) for national planted forest carbon stock reporting obligations under the United National Framework Convention on Climate Change and Paris Agreement Nationally Determined Contribution (MfE, 2021). The carbon stock and stock change data is also used for reporting against the Criteria and Indicators of the Montrèal Process, as well as the United Nation's Food and Agriculture Organisation's Forest Resource Assessment (FAO, 2015; MPI, 2015). C_Change has also been used to support the quantification of carbon ecosystem services provided by planted forests (Yao et al., 2021).

C_Change plus the 300 Index – effectively the FCP (Figure 3) – was used to develop the default Emissions Trading Scheme (ETS) Lookup Tables for radiata pine and is also used to underpin Participant-Specific Tables for the ETS Field Measurement Approach as part of governmental data analysis tools. As well as estimating current carbon stocks for reporting, it is used to develop yield tables for projections that underpin policy development, e.g. the Climate Change Commission report on the development of carbon budgets and emission reduction strategies (Climate Change Commission, 2021). At a forest management level, C_Change (within Forecaster) is used by forestry consultants and companies undertaking carbon investment analysis.

Scion's FCP model is made up of a linked suite of sub-models (Figure 3). The annual biomass pools predicted by C_Change are used as inputs for NuBalM (Figure 3), which models site-specific nutrient sustainability over multiple rotations under different harvest residue and forest floor removal methods.

There is increasing interest in the use of NuBalM to support sustainable precision nutrient management for planted forests in New Zealand. The interest is mainly from the forestry sector to support nutrient management planning for increasing sustainable productivity and from regulatory authorities to predict nitrogen leaching under various new land use scenarios that include forest establishment (Garrett et al., 2021). Moreover, NuBalM is underpinning engagement with the Overseer[FM] model, a model widely used in agricultural systems and more recently by local government regulatory bodies for decision-making related to land use management (Wheeler et al., 2003; MPI, 2020; Garrett et al., 2021).

Improved forest productivity

As an improved ex-pasture site at moderate altitude with generous rainfall, PEF supports one of the fastest-growing forests in New Zealand. PEF has demonstrated a 54% increase in forest productivity in the second rotation (Table 1) compared to the first rotation, and is 63% more productive over the second rotation compared to the national average (for all species) in

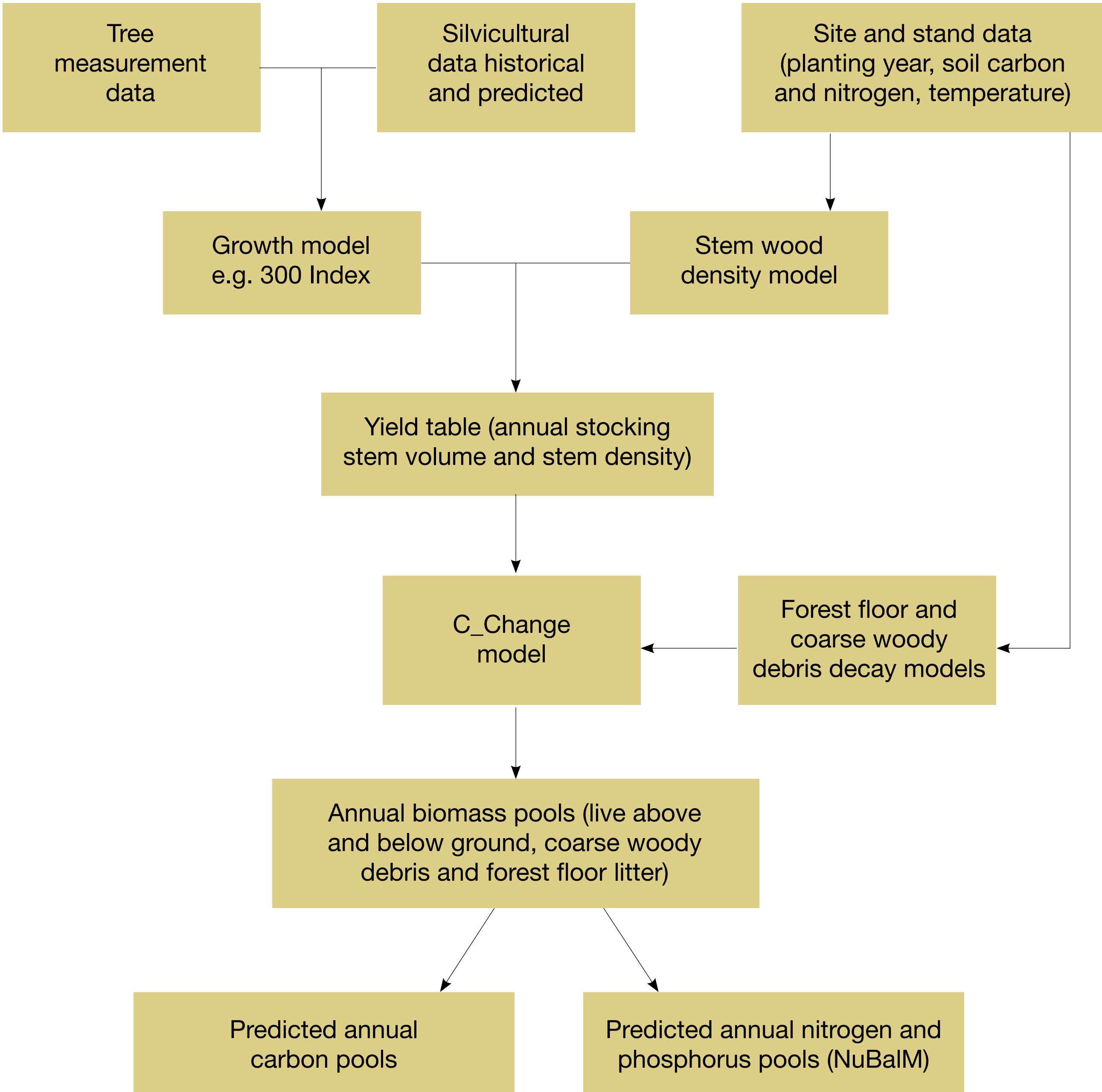

Figure 3: Flowchart outlining the FCP that models carbon stocks and includes the NuBalM to predict nitrogen and phosphorus stocks for New Zealand's planted forests. Adapted from Beets et al. (2011a). The 300 Index model is used to derive the mean annual increment corresponding to a standardised regime with a final stocking of 300 stems ha^{-1} at stand age of 30 years (Kimberley et al., 2005)

post-1989 planted forests (MfE, 2021). This high forest productivity is due to the:

- Inherent site fertility brought about by past application of fertilisers (super phosphates) (Beets et al., 2019)
- Planting of healthy trees (less prone to needle-cast fungus e.g. *Cyclaneusma minus*) and superior growing genotypes at a high stocking rate (Beets et al., 2011b)
- Likely benefit of a harvesting and site preparation for re-planting regime that left the harvest residues and nutrients they contain on-site (Oliver et al., 2004) to benefit the next forest rotation (Garrett et al., 2021).

The value of PEF can be demonstrated through the impact on the forestry sector:

> *'Puruki has shown Timberlands what is possible from a productivity standpoint and really highlighted the importance of forest nutrition. The outcomes from Puruki are helping to inform our research and development programme that is targeting a step change in forest productivity.'*
>
> Dr John Moore, Research & Development Manager (Pers comm)

During the first rotation at PEF, UMCY was a nationwide issue in some forests and stands. UMCY is expressed as a loss of foliage in the upper crown and, if severe, results in crown dieback and productivity loss (Beets & Jokela, 1994). UMCY was particularly prevalent in the 60 SPH catchment at PEF and, along with *Cyclaneusma minus*, was causing considerable foliage loss in many trees (Beets et al., 1997). These observations initiated research toward understanding the large variability in the expression of these two disorders.

Research at PEF established the importance of within site variability of environmental, soil and tree genetic factors in UMCY disease expression (Beets et al., 1997; Beets et al., 2004). Healthy individuals from PEF's first rotation, inferred as showing tolerance to both UMCY and *Cyclaneusma*, were identified and cones used as parent trees for the second rotation Puruki Control (PC) seedlot (Beets et al., 2004). This simple selection for tree health within the same genotype, and then planted at higher stocking, demonstrated productivity increases of 24% (Table 1).

Better understanding of carbon and nitrogen stocks

New Zealand's planted forests sequestered 29 million tonnes of carbon dioxide from the atmosphere in 2019 (MfE, 2021). The rate of carbon sequestration in the growing forest is directly linked to tree growth and site productivity. As PEF is highly productive, carbon sequestration rates are high; second rotation GF30 planting stock are estimated to store ~400 Mg ha^{-1} of carbon at age 26 years in the live biomass and forest floor (Figure 4a). This is in comparison to New Zealand's post-1989 planted forests with a mean total carbon amount at age 26 years of 245 Mg ha^{-1} in the live biomass and forest floor (MfE, 2021), tall natural forest total live biomass and forest floor carbon amount of 252 Mg ha^{-1} (MfE, 2021; Paul et al., 2021) and pasture biomass between 3–6 Mg ha^{-1} of carbon (MfE, 2021).

Comparing the PEF GF30 biomass and forest floor carbon amount (~400 Mg ha^{-1}) to the carbon in the soil at PEF, the soil holds about 38% of the planted forest total carbon stock, 143–164 Mg ha^{-1} of carbon to 1 m soil depth (Oliver et al., 2004). Therefore, at the end of the second rotation PEF will have about 553 Mg ha^{-1} of carbon stored on-site.

The impact of land use change and clear-cut harvesting on the soil carbon stocks has been researched at PEF. With conversion of pasture to pine, 4 Mg ha^{-1} of carbon was lost from the surface soil layer (Beets et al., 2002), but this comprised less than 1% of the total carbon at the end of the second rotation at the site.

Table 1: PEF productivity metrics for tree age 20 years from the first rotation (GF7 at final crop stocking of 500 SPH) and second rotation (range of planting stock, planted at 1,000 SPH with no thinning)

Puruki Experimental Forest age 20 years	Rotation 1	Rotation 2			
	GF7	GF30	HD	PC*	GF2
300 Index (m^3 ha^{-1} yr^{-1})	30	36	32	30	26
Site Index (m)	31	30	31	30	29
MTH (m)	32	30	30	30	29
BA live (m^2 ha^{-1})	60	89	79	72	61
SPH live (count ha^{-1})	518	693	708	676	611
Stem volume live (m^3 ha^{-1})	690	1009	875	814	661
Production stem volume net MAI (m^3 ha^{-1} yr^{-1})	33	51	44	41	33
% increase in production stem volume net MAI compared to GF7 rotation one		54	33	24	1

* GF7 selected for healthy trees; MTH – Mean Top Height; BA – Basal Area; SPH – Stems Per Hectare; MAI – Mean Annual Increment. Note that GF2 seedlings from unimproved Riverhead Forest, Puruki Control (PC) seedlings from PEF first rotation GF7 were selected for health, High Density (HD) and GF30 seedlings from a defined set of control pollinated parents with improved growth and form (Beets et al., 2011b)

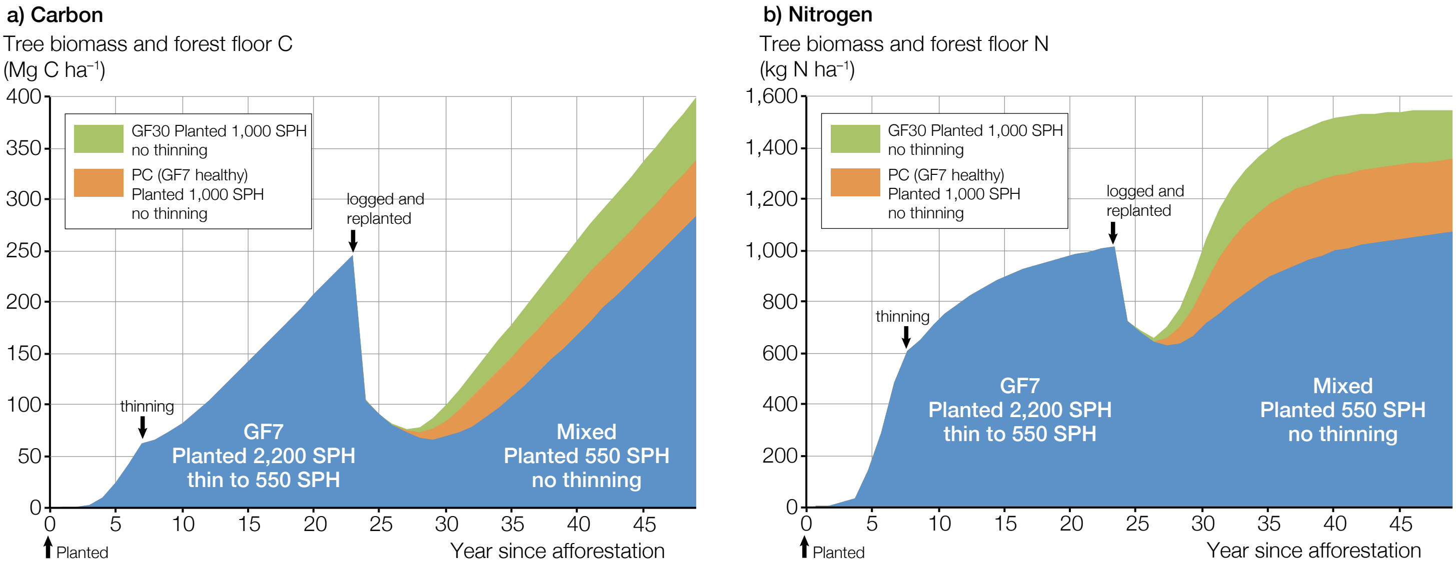

Figure 4: Modelled tree biomass and forest floor (a) carbon stocks and (b) nitrogen stocks over two rotations using the FCP and NuBalM models, respectively. Modelled inputs were the first rotation planted with *P. radiata* GF7 stock at 2,200 SPH, thinned to 550 SPH, and the second rotation planted with *P. radiata* mixed stock at 500 SPH, no thinning, and GF30 and Puruki Control (PC = GF7 selected for tree health) at 1,000 SPH, no thinning. Harvesting extracted the tree stem only, leaving tree crown and stump (slash) distributed over the site

High spatial variability in soil carbon was also found. This was attributed to the past podocarp/hardwood native forest, which was cleared from the site 100 years earlier (Beets et al., 2002), demonstrating the importance of historical and protected carbon in the soil.

Clear-cut harvesting activity of PEF first rotation forest was found to reduce surface soil carbon stocks by 3.1 Mg ha^{-1} due to mixing with sub-soil, but there was no change when the soil was measured down to 1 m depth (Oliver et al., 2004). The work on soil carbon at PEF has supported recommendations on how to sample planted forest soils that have deep-rooting trees and consideration for New Zealand's soil carbon, which can have high variability in soil carbon stocks as a result of the past native forest land cover.

The high fertility of soil at PEF, a legacy of past farming practices, means that the site can sustain highly productive forestry across multiple rotations whilst maintaining nutrients on-site. Results from NuBalM show the first rotation forest at PEF accumulated 1,011 kg of N ha^{-1} in the live and dead biomass pools (Figure 4b), using available nutrient resources only, i.e. without any further additions of fertiliser. The harvest operation extracted the stem only, exporting 150 kg of N ha^{-1} from the site and leaving 85% of the tree and forest floor nitrogen.

The nutrients held in harvest residues and forest floor were supplied to the second rotation pine that had greater potential growth (due to improved genotypes maintained at higher stocking rates), subsequently lifting the overall productive capacity of the site (site quality; Figure 4b). Supported by retaining harvest residues on-site, release of nutrients through natural soil weathering (Garrett et al., 2021) and atmospheric deposits of particularly nitrogen, PEF has demonstrated that a fertile site can sustainably supply the additional nutrients for a more productive second rotation forestry.

Better understanding of water yield and quality

The comparative assessment of the paired land uses on water yield and quality has been a key outcome of the Purukohukohu Experimental Basin trials. With the conversion of pasture to planted *P. radiata*, overall annual water yield decreases by 160–260 mm/year dependent on silvicultural regime (Beets & Oliver, 2007). However, water yield measurements derived from PEF, when compared to the adjacent pasture land, demonstrated how forest cover allowed continued stream water flows during dry summer months whilst mitigating floodwater during high rainfall events with more than a 50% decrease in peak flows (Scion, 2020). Thus, continuous monitoring has revealed that annualised water harvest data obscures key metrics associated with seasonal water supply that support ecosystem functioning and potentially other users of water downstream.

Despite PEF being a highly productive forest on a fertile site, data shows it has low nitrogen and phosphorus losses to stream flow, with levels that are comparable with native forest and much less than that from the neighbouring livestock grazed pasture (Figure 5) (Quinn, 2005).

Experimental forests that monitor long-term changes in water yield and quality are rare in New Zealand (Meason et al., 2019), making PEF and its associated long-term monitoring of particularly high value. As this country's water resources come under increasing pressure with intensification, land use change and the integration of production forestry into mosaic land use landscapes, the importance of such data will dramatically increase.

Extension forestry experiments

The second-rotation PEF included an experimental trial established using improved genotypes (Beets et al., 2004; Beets et al., 2011b). A sub-set of 10 of these genotypes were clones and subsequently planted with other *P. radiata* genotypes in a national long-term experimental trial (FR442) to investigate genotype by environment interactions (Hawkins et al., 2010). The FR442 national trial series was established at 14 sites from 2002 to 2004, with the aim to extend site-specific studies on pumice soils to a range of soil types found nationally.

Summary

PEF has had a significant impact on New Zealand forestry science with large benefits for both the forest industry and government. There is now a window of opportunity to collect data leading into and over the harvest phase of one of the fastest-growing and most productive second rotation forests in this country. This research will contribute significantly to the already valuable legacy of research into forest management and growth modelling that supports the forest industry's social licence to operate. The next phase offers a new opportunity to extend the legacy of PEF by undertaking ambitious ecosystem-level research for the benefit of New Zealand.

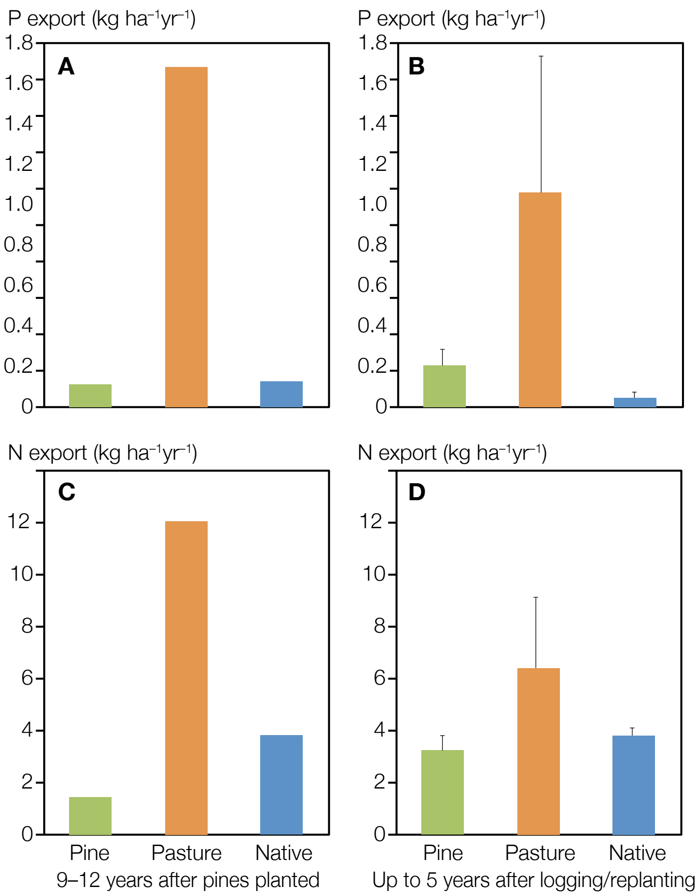

Figure 5: Land use effects on average yields of total phosphorus and nitrogen at Purukohukohu (Quinn, 2005)

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Loretta Garrett is a Soil Scientist, Stephen Pearce a Senior Research Technician and Tim Barnard an Environmental Planner, all based at Scion in Rotorua. Steve A. Wakelin is an Environmental Microbiomes Specialist at Scion in Christchurch and Steve J. Wakelin is a Forestry Scientist at Scion in Wellington. Corresponding author: loretta.garrett@scionresearch.com