THE NUTRIENT IMPACTS OF FORESTRY

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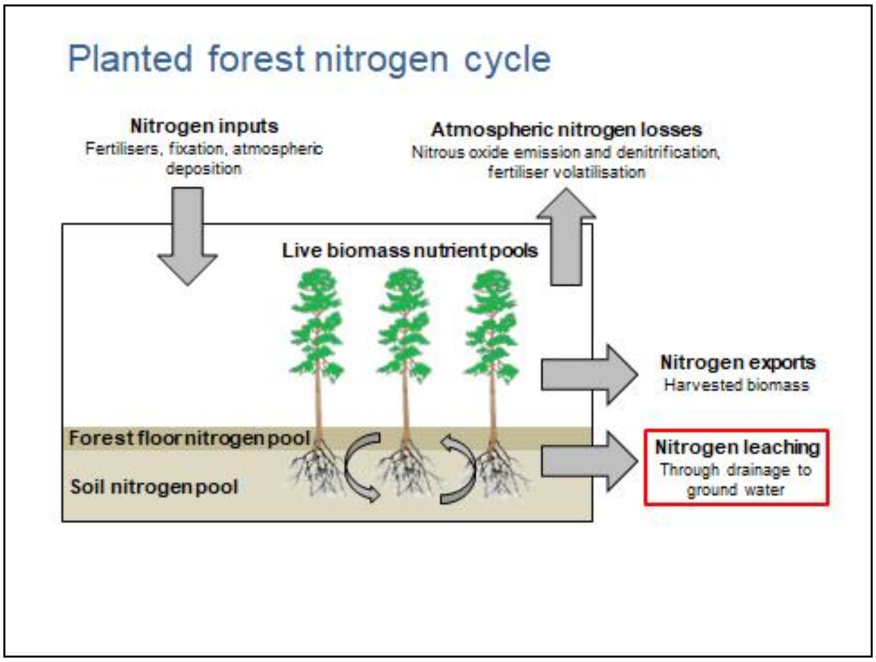
- *Measurement and modelling of carbon stocks and changes in planted and natural forest*
- *Modelling stand productivity, water-use, and nutrient cycling in Pinus radiata*

TRANSCRIPT

Good afternoon ladies and gentlemen. Kia ora
I have had a long history in forestry and it started early as I was raised in a little place called Kaitawa at Waikaremoana. I roamed in the bush when I was a little kid and I have not lost the enthusiasm for trees and forest.

I have been working on New Zealand's Land Use and Carbon Analysis System (LUCAS) for the Ministry for the Environment to quantify carbon stocks and changes for planted and natural forests. I originally started at Scion when it was called the Forest Research Institute working on tree nutrition. It is relevant for me to discuss this topic now because after we put the carbon models together I was able to come back to tree nutrition. I was amazed to find the papers we published years ago were still in journals and not incorporated into models that we could use for tree nutrition. I suggested to the managers that it was time for me to put away administrative things and managing projects and focus on reading all those publications, not just from Scion, but other agencies too and put them into models. We are making progress.



A model is just a representation but to understand what happens in a planted forest you have to remember that they are very dynamic. The title was 'Forestry Impacts', which means a management component. We know that trees are planted, they grow, they accumulate biomass and nutrients that cycle around and you can see that in the flow diagram. There are nitrogen inputs coming from the atmosphere and nitrogen taken up from the soil, which accumulate in live biomass and dead matter in the forest as it grows. Some nitrogen can be exported in harvested logs but how much of that nitrogen in the forest ecosystem can leach?

There have been reviews of factors that influence forest nutrient cycling and leaching losses and what the forestry impacts are. Davis (2014), and Baillie and Neary (2015) showed that land use history is one of the important things to consider when looking at forestry's impact. It may be different from what you might expect but the fertility of the site is key. When trees are limited in terms of nutrition they take up nitrogen very efficiently. You do not expect nitrogen to leach out of a forest plantation that is short of nitrogen.

LU history - unimproved shrubland with C/N = 24: N & P loss to ground water are minimal

Knight and Will (1977), Warsnop and Will (1980) - lysimeter drainage water quality, Kaingaroa Forest, Pumice soil)

Parameter (loss kg/ha/year)	Age 1-3 years after harvesting	Age 6-12 years	Age 14 years (2nd year after fertiliser applied)
NO_3 – N	4.8	0.0	0.006
NH_4 - N	0.0	0.0	0.005
PO_4 - P	0.096	0.007	0.0

Rainfall averaged 1500mm

Drainage occurred Sept/Oct each year, and commonly in June-Oct

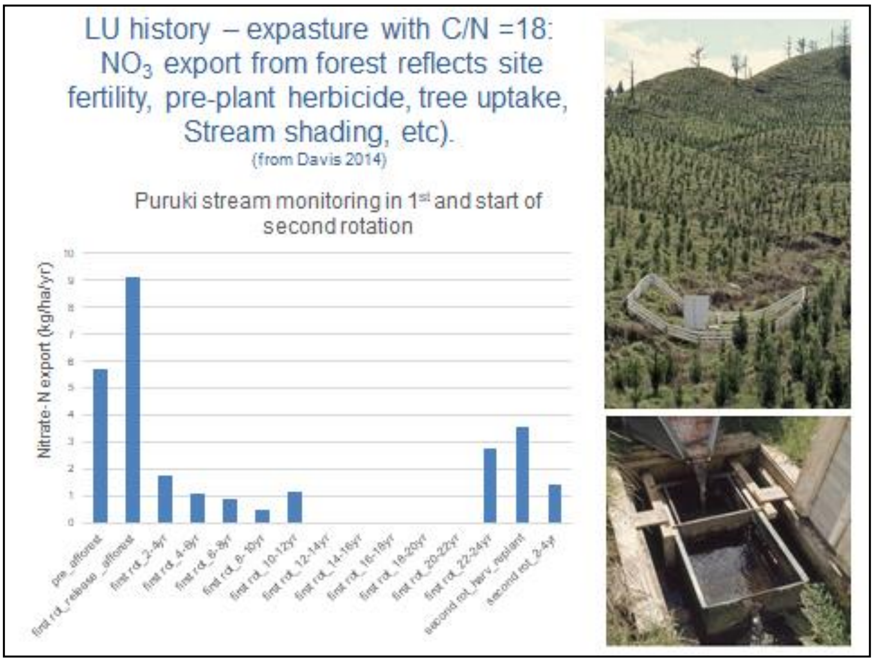
200kg/ha of ^{15}N enriched urea applied Feb. 1975 (13 year trees)

- Monitored for 3 years: virtually no N leached to groundwater
- NH_4 – soil elevated in week 1 (maximum in week 4)
- NO_3 – surface soil elevated in week 2 (persisted for 3 years)
- Week 2: 90% of N recovered in forest floor/soil to 30cm
- Week 4: 60% of N in floor/soil, and 50% after 3 years
- Timing and method of application minimized losses
- Trees accumulated 100kg fertiliser N/ha - demand > supply

The Kaingaroa Forest is an example of a forest not overly rich with nitrogen. It has had a history of shrubland (not a farming history) so nitrogen availability is quite low. A lysimeter study that collected water draining from the soil under the forest showed that zero nitrogen leached from this forest once the tree canopy had fully developed. The tree demand for nitrogen is too high at that stage to allow nitrogen to escape. This lysimeter study also showed that even after nitrogen fertiliser was applied to the soil to improve tree growth, hardly any nitrogen leached from the soil. For nitrogen to leach there has to be water draining from the soil. The fertiliser was deliberately applied in summer (February), when trees use lots of water, and soil moisture storage capacity was sufficient at that time to prevent drainage from occurring. So even though there was nitrogen as nitrate in the soil surface, it did not leach. Nitrogen moved deeper down in the soil profile but we also know how deep roots are. The rapidly growing trees had sufficient time to take up this nitrogen.

When tree growth is interrupted following a harvesting operation suddenly there is a completely different ecosystem. New trees are planted but their nutrient requirements are initially very low and nitrogen levels in the soil water increase. All sorts of weeds grow back rapidly, using some of this nitrogen, and there is spraying to control weeds. Tree evapotranspiration is low because there are hardly any leaves on the young pine trees in the first few years. Evapotranspiration is the amount of water the pine forest is using. Drainage therefore increases following harvesting and more water moves down through the soil beyond the reach of tree roots. The newly planted trees do not take up all of the available nitrogen so some nitrogen leaches at that stage.

A very fertile site is quite a different story. Does the supply of nutrients exceed the requirements of trees? If it does that excess nitrogen is not used and will leach under the type of soils that we have.



Here we see a little data series of stream nitrate exports when a fertilised pasture catchment is converted to pine forest. These are called land use history catchments. The Puruki experimental catchment was set up as part of the international hydrological decade. There were several catchments in this 1960s study, and this site has been monitored almost continuously since that time. Where the young pine trees are growing used to be pasture. There is an adjacent catchment left as pasture. There is also a native forest catchment there so it is a very interesting study.

There were lots of agencies that worked here including NIWA and scientists at the Water Quality Centre. A lot of data was collected. Interestingly in those days researchers seemed to be partitioned in what they were allowed to do. The Water Quality guys worked on streams and measured the quality of the water. We were forestry people and our focus was on measuring the forest. It is curious now because, as we have heard over the last few days, what goes on in the land determines what is going to happen in the water. One wonders why the separation. The good thing about this study was that it was an interdisciplinary interagency programme and allowed us to talk to each other and find out what was happening. As the data was collected there was plenty of discussion going on.

The graph shows that stream water nitrate levels vary markedly over time. The series begins pre-afforestation when the catchment was still in pasture, continues after tree planting, and ends after harvesting and replanting of the catchment. The area was sprayed prior to planting the trees, to release them from competition, and there is an obvious pulse of nitrate in stream water at that time. You all remember what happened at Hubbard Brook[1] don't you? If you keep on spraying, a lot of the nutrients will leach out. Then the trees grow quickly and there is a rapid reduction in the nitrate in stream water. Unfortunately there was a gap in the record. Water Quality monitoring commenced again just before the trees were harvested, when it was apparent that nitrate nitrogen in stream water had slowly increased as the trees became mature. This time series indicates that forestry has different effects at different times in the rotation. It is not just 'here is a forest effect and there is a pasture effect'. In a managed forest, tree requirements for nitrogen change over a rotation. Nitrate nitrogen that is not being taken up leaches from the soil and drains into the stream.

When the harvesting operation occurred, this tree age-related pattern repeats itself. Interesting pattern isn't it? To understand it, in the next few slides we will look at the nitrogen cycle in a managed forest more closely, but before doing this, one more piece of research is helpful to consider.

LU history – ex-pasture with C/N =18:
Soil water versus stream export (1984 with 11yr old pine) of N, P, and ratios for pasture versus pine
(from Cooper and Thomsen 1988)

Land use	Parameter	Soil loss (in springs) kg/ha	Stream loss (catchment baseflow) (kg/ha)	Stream loss (catchment total flow) (kg/ha)
Purutaka pasture	NO_3 – N	8.1	0.29	1.19
	DKN	0.15	0.72	2.62
	Total N		1.15	11.95
	DRP	0.13	0.037	0.37
	Total P		0.122	1.67
	TN/TP	63.5	9.4	7.2
Puruki pine forest	NO_3 – N	1.23	0.4	0.55
	DKN	0.43	0.19	0.52
	Total N		0.63	1.31
	DRP	0.07	0.017	0.036
	Total P		0.038	0.095
	TN/TP	23.7	16.6	13.8

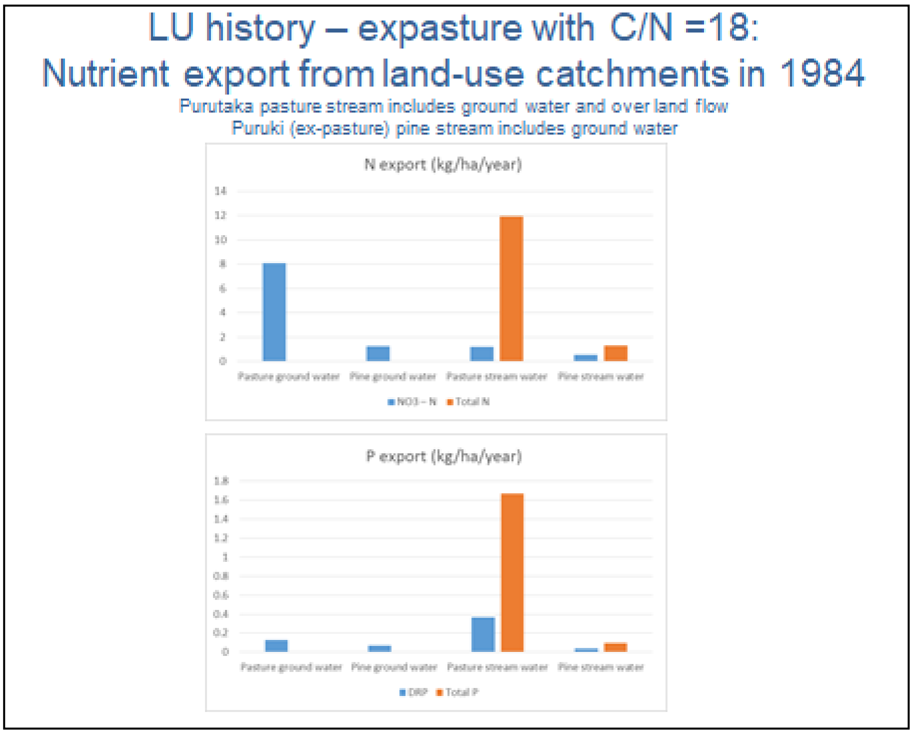
[1] https://hubbardbrook.org/ At the 8,000-acre Hubbard Brook Experimental Forest in New Hampshire, long-term studies of air, water, soils, plants, and animals have produced major discoveries about human and natural disturbances to the forested landscape of the northeastern United States. In a collaborative research project spanning nearly six decades, scientists have discovered the existence and origins of acid rain; unlocked the mysteries of lead, salt, and nitrogen pollution in streams and lakes; and charted the rise and fall of bird populations because of climate change and other threats. Research findings at Hubbard Brook provide the raw material for education and policy-outreach programs that deliver authentic data to students, policymakers, and members of the public who care deeply about our natural world. Hubbard Brook is much more than an ecological field station in New Hampshire—it represents a new paradigm of 'ecosystem thinking' that has changed the way we understand how nature works.

The previous slide is the work that Bryce Cooper and colleagues did showing soil (ground) water versus stream water export of nitrogen and phosphorus at Puruki. The trees were 11 years old at the time they did this study which showed that ground water draining from a pine forest catchment (that used to be pasture) contained much less nitrate than ground water draining from an adjacent pasture catchment. Why is that? The modelling work that comes next shows that 11 year old pine require a large amount of nitrogen, most of which comes from the soil. In the stream is a different story. In fact ground water and stream water monitoring tell different stories. What is it they are telling? As water trickles down the stream channel changes can occur in the form of nitrogen.

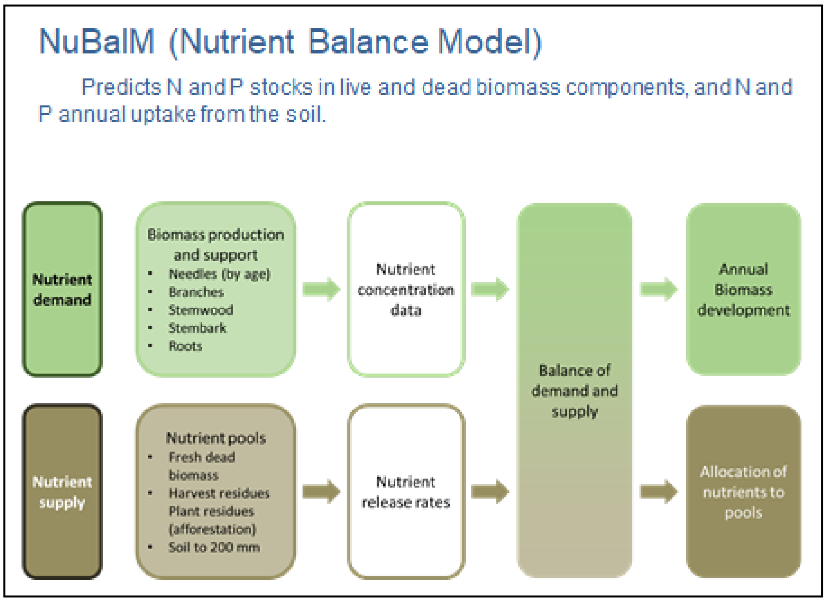
The relatively high levels of nitrate in ground water draining this pasture catchment were markedly reduced after entering the stream. That is the in-stream processing where vegetation growing in the stream channel takes up nitrate and stores it as organic matter before it even reaches the weir where measurements of nutrient exports are made. Organic forms of nitrogen from the vegetation growing in the stream channel are still exported, but this occurs mostly during storm events, which explains why the total nitrogen export from the pasture stream is high.

It is a similar story for dissolved phosphorus in ground water. However, total phosphorus export increases markedly from the pasture catchment when overland flow transports additional P, presumably from animal waste, during intense or prolonged storm events, which was not evident in the pine catchment.

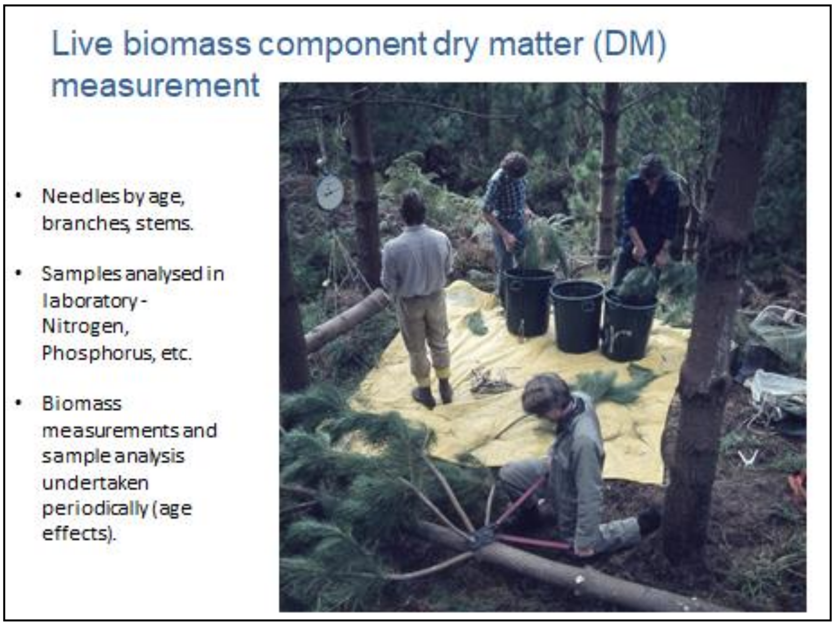
Unlike the pasture catchment, forest cover largely shades out vegetation that would otherwise grow in the stream channel, and in-stream processing of the nitrate in ground water that enters the stream does not occur. Therefore the export of both nitrate and total nitrogen from the pine catchment is low, as is the export of total phosphorus.



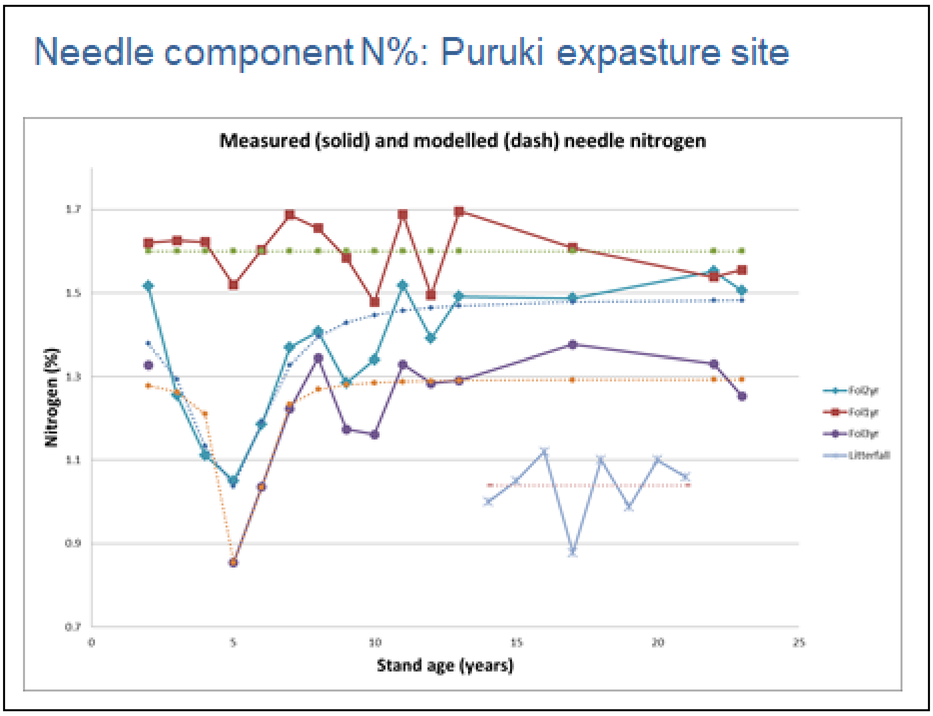
This slide shows a nutrient balance model (NuBalM) which has been developed for radiata pine to help explain and predict what goes on as a forest grows. We have biomass, the representation of different parts of a tree and nutrient concentrations which are needed to estimate N and P uptake from the soil. There is also dead material accumulating and decaying on the forest floor, which cycles nutrients including N and P back to the trees.



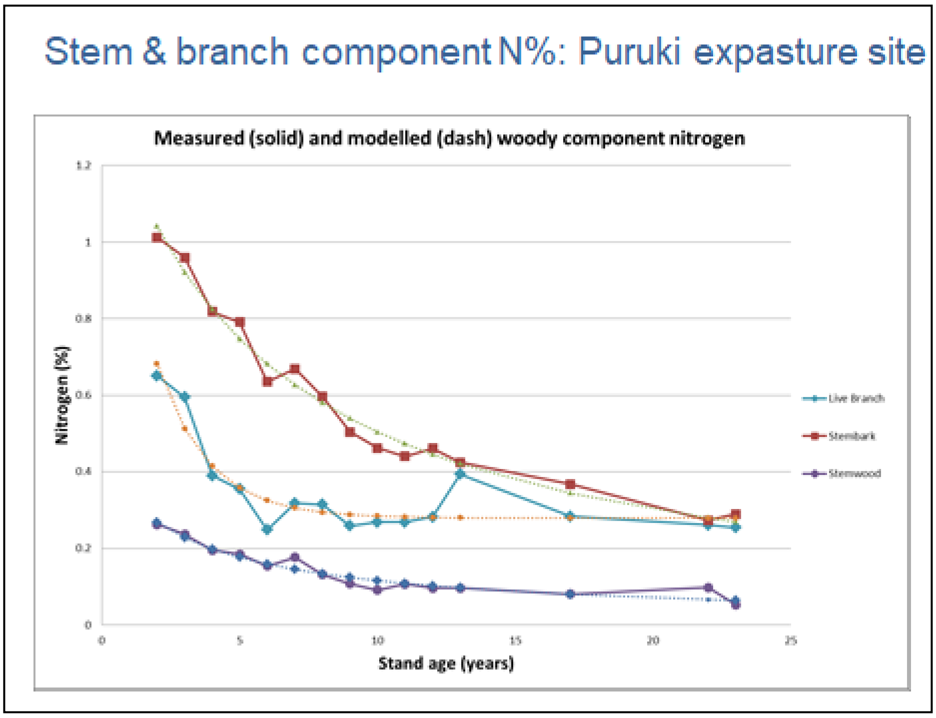
To get that kind of data you have to pull trees apart, age the needles, look at the different components such as the branches, stems and root, to work out how much requirement there is for nitrogen as a forest grows. Samples are divided into different components and analysed to look at their nutrient concentrations.



The new and old needle growth was measured and there is a big drop in concentrations between the two ages of needles when the trees are 5 years old but not later on. That is interesting. The litter fall comes when trees let older needles fall.



We also looked at how much the stem wood, stem bark and branches take up by tracking the concentrations in these components. Going back to the same forest year after year and re-measuring another sample of trees gave us data for modelling nutrient uptake.



The next slide shows the forest floor litter layer formed from the needle fall measurements in un-thinned and thinned pine stands. The most interesting information is the average value of 0.5, which states that the rate at which needles in the forest floor turned over nitrogen is half the rate at which the carbon turned over. In other words, the litter is rotting away but the nitrogen is retained for twice as long. That has implications on the graphs that follow.

Litter N%: Puruki expasture site

Puruki Subcatchment	Forest floor (LFH) pool at age 22 years (excl. dead branch)			Average annual needle fall from age 14 – 21 years			Turnover rate		
	DM (t/ha)	N (kg/ha)	N (%)	DM (t/ha/yr)	N (kg/ha/yr)	N (%)	DM	N	Ratio N:DM
Plant 2200 sph, unthinned	35.9	762	2.12	6.33	70.8	1.12	0.18	0.093	0.53
Planted 2200, thin to 676 sph	23.5	509	2.17	5.15	53.4	1.04	0.22	0.105	0.48
Average									0.50

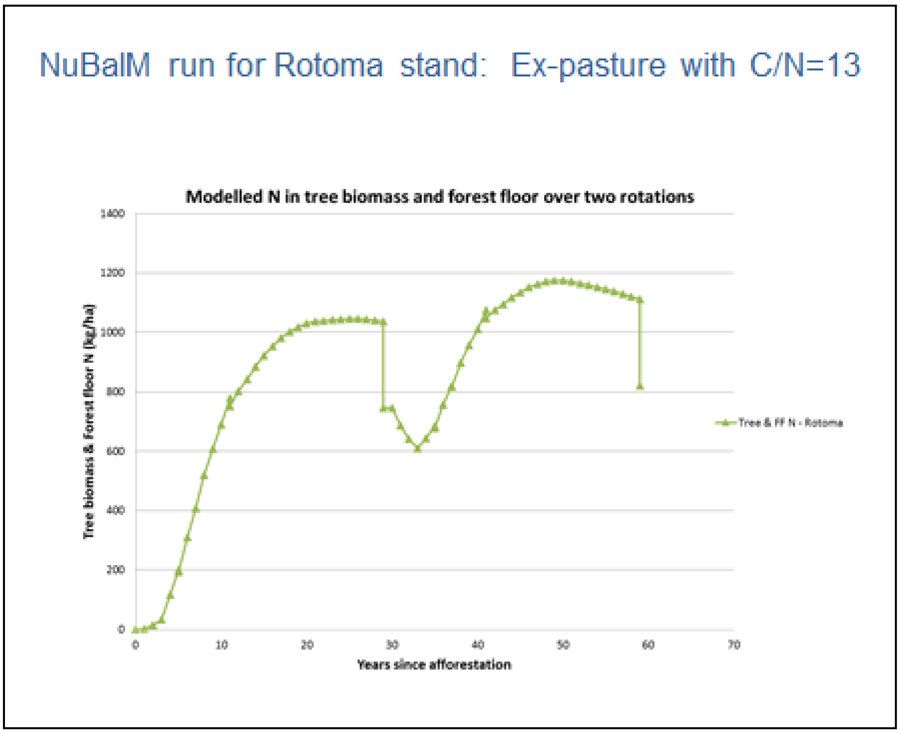
- Needlefall measured continuously (1987-1994).
- Forest floor measured in 1995 (to determine turnover rate).
- Nitrogen turnover rate expressed relative to dry matter turnover rate.

This shows the result of modelling nitrogen in live tree biomass in a first rotation stand at Rotoma. The tree biomass takes up over 600 kilos per hectare by the time the trees are about 30 years old. Pruning and thinning operations at Rotoma cause the periodic drops in nitrogen (saw tooth effect), which are followed by recovery of N in the tree biomass

NuBalM run for Rotoma stand: Ex-pasture with C/N=13

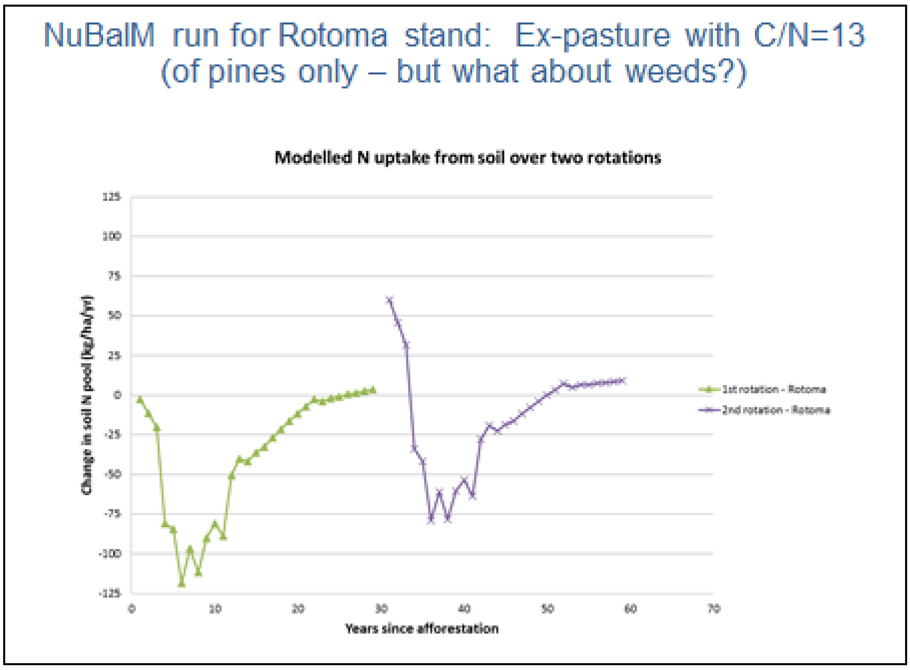
This shows the total nitrogen (live biomass plus forest floor) in a first rotation stand (climbing to just over 1000kg/ha) followed by the second rotation (about 1100kg/ha). At harvest there is a decrease in nitrogen (nitrogen in harvested logs is removed off-site and harvest residues decay) and then nitrogen climbs back up again as the second rotation trees grow. With the subsequent regrowth of trees nitrogen accumulates to over 1,000 kilos per hectare after 50 years. All that nitrogen comes from the soil, except a little bit from atmospheric inputs.

You would have seen harvest residues at a harvested site - they provide the nitrogen for the second rotation. The sudden drop at about year 30 results from removing the nitrogen as logs. The first rotation tree crop does most of the work of pulling nitrogen directly out of the soil and the second rotation relies a lot on recycling of nitrogen in harvest residues. This information has interesting implications in the longer term if the intention is to continue to draw down excess levels of soil nitrogen to reduce nutrient leaching.



This slide gives an idea of turning the nitrogen accumulation graph (the previous slide) into the annual nitrogen demand from the soil. The slide does not show the stock of nitrogen in the soil, but the change in stock (negative values mean the soil nitrogen stock decreases by the amount shown). So, how much is the forest needing out of this soil each year? At around about age 5 or 6 (1^{st} rotation) the soil must supply about 100kg per hectare per year. That is a lot of nitrogen. You will then notice that, from age 10 – 20 years the annual nitrogen requirement from the soil gradually decreases (slowly becomes less negative). That is because nitrogen is increasingly being cycled through the litter fall and cycling through the forest floor.

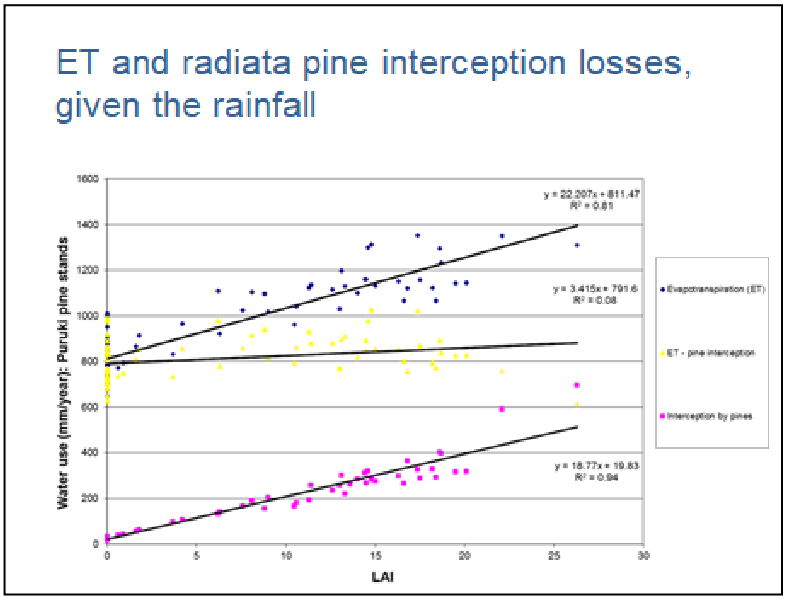
The annual demands on the soil eventually decline right away as the trees get older and rely increasingly on nutrient cycling. This nitrogen uptake pattern repeats itself in the 2^{nd} rotation. However the demands on the soil are not as great now because the decaying harvest residues left on site provide nitrogen. In fact, the positive values at the start of the second rotation indicate that the amount of nitrogen released from decaying residues exceeds the annual requirements of the newly planted trees. Some of this nitrogen will be taken up by weeds and the rest will leach if soil water drainage is occurring.



To test the model, we used the NuBalM Water Balance Module at Lake Rotoma to see what is expected to happen. Rotoma had pine plantations recently harvested right near the lake. Working with the Bay of Plenty Regional Council, using lysimeters, we wanted to know how much nitrate nitrogen was in the surface soil water both prior to and after harvesting. The intention is to look at nitrogen leaching to the lake.

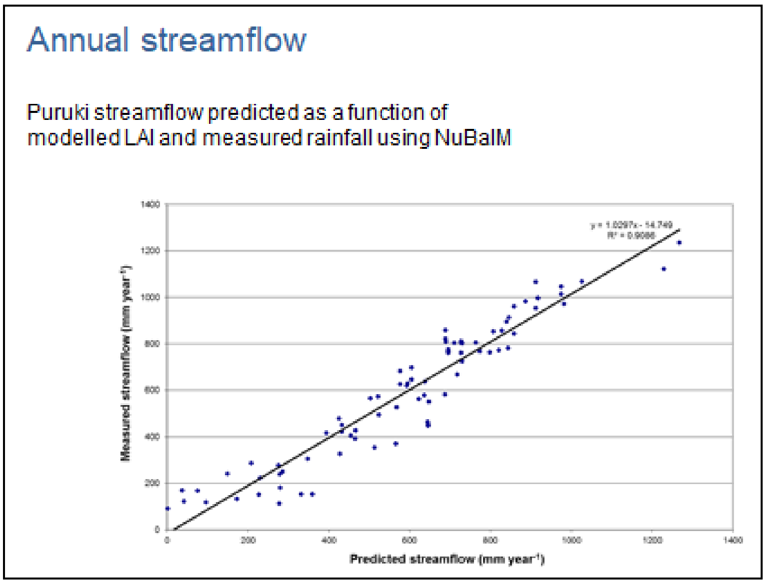
To get nitrogen leaching there has to be nitrate in the surface as a measurement. We have got a measurement of 1.29 milligrams of nitrogen per litre from these lysimeters at 1 metre depth. Then you need to have water draining through the soil to take the nitrate out. There is plenty of water fluxing through the soil at Rotoma (drainage is 985mm/year) when there is that much rainfall. Nitrogen leaching, based on calculating the concentrations at that one metre depth, is 12.7 kg/ha/year. We have ground water bores installed at Rotoma to compare with loss estimates based on lysimeters. Lysimeters 1 metre from the soil surface do not allow for tree uptake below 1 metre depth.

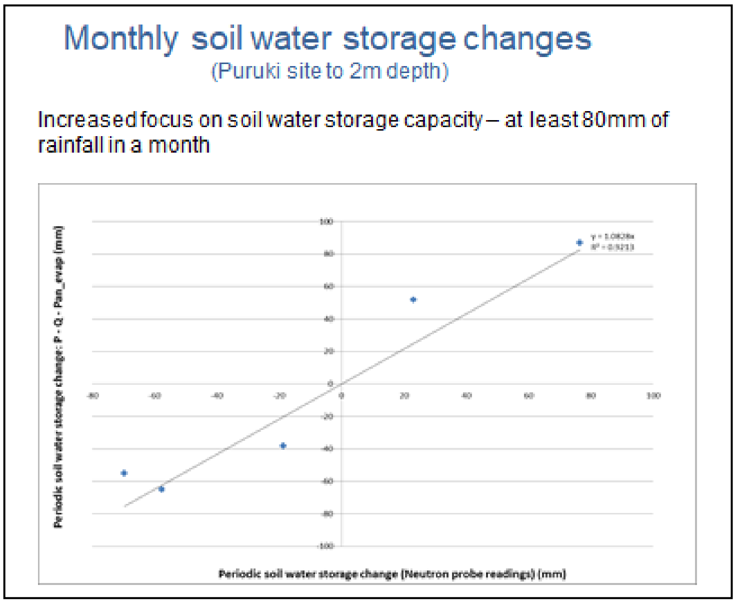
This shows a road cutting to look at how far down tree roots go. There are masses of fine roots well below 1 metre depth. When measuring the concentration of nitrogen in the surface, it does not mean it is necessarily going to leach to the lake. There is plenty of opportunity for the deep rooted species to grab hold of nitrogen before the soil water moves below the root system.



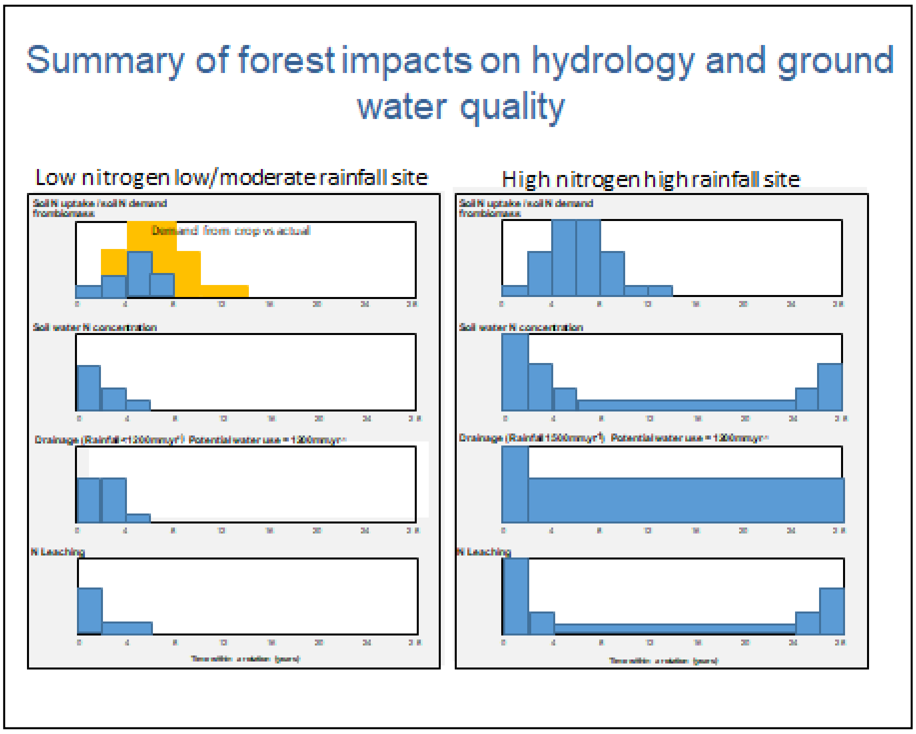
We can work out the drainage rates from a forest because we can calculate how much water is used by the forest from its leaf area (LAI). These three slides are based on the international hydrological decade study at Puruki. In this slide there are many layers of pine needles stacked on top of each other (that's the LAI = 20 when the tree canopy is closed) intercepting about 350 - 400 mm of rain. Intercepted rain evaporates before it reaches the ground. Evapo-transpiration (ET, is overall water use including interception loss) by forest is therefore higher than pasture because forest has higher interception losses. When there is 1600 mm of rainfall and the leaf area index of the pine forest is 20, evapo-transpiration is 1200 mm. Take that off rainfall and there is drainage (or streamflow) of 400 mm.

The slide below compares measured streamflow with the predicted drainage from the model. With 1600 mm of rainfall, drainage from the pasture will be about 800 mm, which is double that from a closed canopy pine forest. So that is why water use of forests is higher than farmland, which some people complain about. But it means that soils under forests are not as wet as those under pastures and can therefore accommodate more and larger storms.





The above slide shows that soil water storage can vary by about ±160 mm from one month to the next at Puruki. Depending on how wet it is, the soil content can absorb rainfall events of 80 mm or more without any drainage occurring. Those sorts of things have to be brought into the modelling to be able to predict nitrogen leaching.



The above diagram shows the main principles around nitrogen leaching that I want to summarise with respect to tree demand, soil nitrogen supply, and drainage.

Left panel: At a low nitrogen site, trees still demand a lot, they want to grow fast, they are pine trees growing but there is not enough nitrogen in the soil for them to take up. The nitrogen uptake is less than what they demand and cannot get. Can nitrogen leach then?

No. Of course early on there is hardly any leaf area and tree demands are still very small, so nitrogen supply from the soil exceeds the demand. That is when there is some leaching loss at low nitrogen sites - in very young stands after harvesting. Water comes in as rainfall, nitrogen is in the soil water and water comes through because there is not much leaf area on a young pine tree. That leads to nitrogen leaching.

Right panel: On a farm site planted with trees in an area with excess rainfall, leaching is quite different, the tree demand for nitrogen now being fully satisfied by that rich soil providing the nitrogen. There will always be some nitrogen left over in the soil water. This will drain away and some nitrogen leaching losses occur every year. The pattern of nitrogen leaching loss mirrors what we saw in the stream data on page 3 where a peak loss of nitrate (when the trees were small) is followed by a rapid decrease in leaching loses as the tree demands go up. There is a little climb later towards the end of the rotation, which the model predicts will happen because more demand is met through nitrogen cycling.

Sediment is probably the most difficult issue for forestry to deal with. Harvesting is the only time in the life of a stand where there will be more water coming off per hectare in drainage water than when there is pasture. For the rest of the time the trees will use more water than pasture. More water run-off means there is a greater potential for sediment loss.

This shows endeavours at Rotoma to trap sediment, considered to be needed in case the dry gully begins to flow. If we start planting more forests in lake catchments we need to consider sediment mitigation options. This issue has not been fully explored yet in terms of smaller wood lots with respect to the new National Environmental Standards. It will need to be looked at very closely, particularly around harvesting. Rotoma is one of those dreaded dry catchments that hopefully does not become a raging torrent in downpours. I do not think it is a sensible to plant up farm stream gullies that will later be harvested. Where would you put in a forest? Trees do not need fertiliser on ex-pasture sites.

This summarises some of the benefits of having forest on farms to reduce leaching losses to ground water:-

Soil fertility

- Trees do not need to be fertilised
- N and P leaching losses diminish relative to pasture land use
- Forest demands on soil nutrient reserves are large in first rotation but small in the second rotation (with stem only harvesting)
- Research shows that soil nutrient depletion occurs using more intensive organic matter removal practice or intensive biomass harvesting (eg. for energy) – is this desirable?

- The challenge is to close the cycle - fertiliser inputs to farm could be reduced by cycling nutrients trapped by trees back to pasture
- How? Tree species for silvo-pastoral systems (fodder). Litter raking (bedding)

Sediment issues

- Run-off increases when harvesting. Sediment transport control options need to be considered

In the old days they used to litter rake for bedding which was used under stock in their yards. Litter raking reduced forest productivity, until that practice was banned in some countries. It is an example to show that nutrients can be drawn down by removing and raking all the forest floor away, and accentuating the drawn down in areas where there is too much nutrient, which might be in zones where nutrients are trapped.

I talked about pine because we have lots of data but there are other tree species and silver pastoral systems that could be considered. Apples and all sorts of woody vegetation used to be grown with pastures. It was not all pure pasture but mixed up and the variety of species provided key nutrients. We bring in palm kernel for key nutrients. I do not know why. Why not grow other species to do that?

The NuBalM model development research described in this presentation is funded by New Zealand Forest Owners through the levy. Every grower of a stand pays the levy when the trees are harvested. Research now is focussed on linking this modelling system to different types of soils around the country but it is mostly focussed around here at this stage.