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Analysis of long term productivity and productive capacity of a radiata pine plantation on infertile fine textured soils

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Prepared for

Forest & Wood Products Australia

by

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Abstract

Long term changes in productivity, productive capacity, carbon accumulation and hydrology have been studied at the plantation level at Lidsdale State Forest, NSW. The plantation was initially established in 1920. The study involved a number of projects for which data collection commenced in the 1960's. The studies involved the pine (Pinus radiata) plantations and also adjacent native forests where the data were used as baselines to evaluate the impacts of the pine plantations. Results are summarised below and there are links to full reports on each project and related publications.

Some key points arising from the study were:

1. *The native forest catchments were used to benchmark changes in the pine plantations for productivity, carbon and nutrient change. In the mature eucalypt over 33 years (Catchment 5), the vegetation and soils accumulated carbon at 1.1 tonne C/ha/yr. Nutrients (N, P, K, Ca and Mg) were redistributed within the catchment over that period and N had an apparent accumulation of 8.5 kg N/ha/yr (Johnson and Turner 2013).*

2. *In the pine catchment studies, the mature pine catchment accumulated carbon at 2.14 tonne C/ha/yr between ages 42 and 55 years and most of this was in the vegetation. The site was cleared and replanted and the subsequent rotation accumulated carbon at a rate of 5.5 tonne C/ha/yr in the first 12 years. In Catchment 6 which was established as first rotation pine up to age 34 years, the accumulation rate was 8.9 tonne C/ha/yr. The plantation was not thinned in this period.*

3. *A series of plots used for productivity analyses in the first rotation in 1961 were re-assessed using the same methodologies in the subsequent rotations. The plots were across the plantation and growth was measured and soils and foliage samples were collected. Productivity was relatively low. Where no significant quantities of fertilizer nutrients were applied in the second rotation, the second rotation productivity was lower than the first by 5-8%, probably as a result of nutrient removals (Turner and Lambert 2011). Where significant quantities of phosphatic fertilizer had been applied in the second rotation, productivity in the second rotation was higher than the first by more than 30% but this was lower than expected based on fertilizer trials. The applied fertilizer had a residual effect on productivity into the third rotation (reported in Turner and Lambert 2013). Through a rotation length of a nutritional management plan it is possible to further increase the productivity of subsequent rotations.*

4. *Based on first rotation soil/productivity models, the productivity of the second rotation was estimated using soils data from the second rotation as an input. That is, are any changes occurring in soil properties reflected in changes in plantation productivity? The functions were used as indicators of changes in productive capacity. The changes in soil properties explained a large proportion of the changes in productivity, both declines and increases, in the second*

and third rotations. Long term productivity changes (that is, rotation length) were mainly related to soil cations, especially calcium. Expected changes in the second rotation relative to the first where productivity was less than expected, were analysed taking account of environmental differences, soils, management and genetics.. Gains from genetic improvements across the plantation were difficult to identify.

5. *The plantation was low in nutrients and there were significant growth responses to applied nutrients at the time of planting and later in the rotation. Responses to any application depended on the rate of application, the fertilizer history and the age of the stand. Significant applications of phosphate (40 kg P/ha or more) had long term effects on productivity and there were residual impacts in the following third rotations. Other than removals of nutrients in harvesting, nutrients that had been applied were retained within the system as estimated from long term budgets.*

6. *The hydrology studies showed that clearing of vegetation led to increased runoff but this increase declined as the stands developed. During the rapid growth phase of the plantation, there were reduced flows and then they started to return to pre-clearing conditions. The quantified effects depended upon the vegetation type and time of clearing and the soil properties. Small catchments for which vegetation changes occurred in the catchment in one year, had large changes in flows, however, larger catchments for which clearing and planting occurred over a number of years and in which the entire catchment was not affected had much smaller changes in flow. The data were used to study stand level water use efficiency and no significant differences were found between forest types. Differences in runoff in relation to vegetation were as a result of interception differences, stand age, and productivity.*

7. *Nutrients affect productivity differently at different stages in the rotation. There needs to be whole of rotation and inter-rotational planning of nutrient management to obtain optimum results from site specific management, especially where there are multiple products.*

8. *Related Publications*

   Johnson, D.W. and Turner, J. (2013). Nitrogen budgets of forest ecosystems: A review. For. Ecol & Manage. (In press).

   Turner, J. and Lambert, M.J. (2011). Analysis of nutrient depletion in a radiata pine plantation. For. Ecol & Manage. 262: 1327-1336.

   Turner, J. and Lambert, M. (2013). Analysing inter-rotational productivity and nutrition in a New South Wales radiata pine plantation. New Forests 44: 785-798.

   Turner, J. and Lambert, M.J. (2014). Water use efficiency in forests. Australian Forestry (In press).

Section 1. Introduction

Maintenance of productivity is a critical issue in the long term management of forest plantations and has attracted considerable attention (Evans 1994; Richardson *et al.* 1999). While the simplest concept involves maintaining a continued flow of timber products from a forest, such as sustained yield, in practice it is a much more complex issue matter. The definition of sustainability varies but includes continued balance in the production of timber, carbon, water and other values. Other issues involve the quantitative analysis of long term productivity of a plantation and identification of causes of any changes.

Long term productivity and inter-rotational comparisons have been undertaken on a number of research trials but analyses at a broader level have proven difficult, often because information has not been retained. The present study is primarily an attempt to identify inter-rotational productivity changes in a radiata pine plantation but also considers approaches in methodologies of analysis.

Section 2. Background to the Study

A fundamental issue in plantation management is ensuring sustained productivity. Plantings of pine commenced in N.S.W. in 1914 and became a major undertaking after 1916 (Henry 1963). With notable exceptions, pine plantations were productive and provided softwood timber which was not naturally available in Australia. However, in relation to the long term productivity (that is, sustained productivity over successive rotations), the relative use of water and the sequestration of carbon are issues that have been raised. The analysis of inter-rotational productivity raises issues on the definition of sustainability and its measurement, in addition to estimation of productivity.

The study was undertaken at Lidsdale State Forest primarily due to the history of research and the potential availability of long term data from the forest. Historically, the Forestry Commission of NSW commenced planting land as accessible as possible to future markets, of which Sydney was the most important. The only land initially available was recognised as being of poor quality, consisting chiefly of nutritionally poor Hawkesbury sandstone, but efforts were made to select the best available land with the view to converting otherwise valueless land to profitable use. While poor soils were chosen of necessity, all plantation sites were carrying native eucalypts of at least 12-15 m in height.

The apparently satisfactory growth of *P. radiata* on poor sandy soils for the first few years after planting at both Tuncurry in New South Wales and extensive areas in South Australia, proved misleading. The 1920-1931 plantations were located in the south-east highlands and the country west of the Blue Mountains; this included Lidsdale State Forest. Criticism against the policy of planting exotic pines culminated in 1935 with the amended Forestry Act which brought the coniferous planting enterprise under direct Ministerial control. The operations ceased and a comprehensive review of the results of the 15 years of planting was ordered. The determinations of this review included immediate abandonment of seven plantations, abandonment of four (including Lidsdale) at the end of the rotation, tending of three, maintenance and extension of the remaining seventeen with one in doubt. While the requirements of the Second World War modified the policy with regard to the future of plantations, the attitude towards factors affecting productivity is best illustrated by evidence submitted to the Rural Reconstruction Committee (Henry 1963): "*Forestry uses climate and the closed canopy and mycorrhiza to fertilize its soils: the farm fertilizer has small economic place in silviculture*".

Detractors of plantations claim they lead to site degradation (citing factors such as acidification, nutrient loss), long term changes in water quantity and quality, and that the overall productivity of plantations declines with time. Proponents indicate that apart from the economic benefits of plantations, the sites are maintaining or increasing productivity through technical improvements in genetics, competition control and nutrition, and more recently, are significant in carbon accretion. Analyses of these have generally considered individual components on a small scale, usually research trial level as opposed to the forest or management unit level. In such situations, the analyses of temporal change, or the interactions of various components or the evaluation of management options have been difficult to undertake. Long term data for different components (growth, productive capacity, and hydrology) are not available in many locations.

O'Herir and Nambiar (2010) reported on long term productivity of radiata pine on sandy soils in the Green Triangle, South Australia. This study has relevance to the present project as it provides a contrast, that is, deep sands compared to clay soils derived from conglomerate and shale. Smaller scale studies have been undertaken on growth of pine plantations (for example. Evans 2005; Long 1997) and soil and nutrition changes (for example, Turner and Lambert 1988, Smith *et al*. 1994) with somewhat variable conclusions probably related to site differences (Turner *et al.* 2001).

Analysis of sustainability requires an understanding of forest production (wood, bio-energy, carbon, water), what controls production and the interaction of these factors and how management can modify these to meet specific objectives. These factors have been addressed in a number of studies at the research level such as: (1) the relationship of soil to productivity, (2) changes in soil properties as a result of plantation establishment, (3) effects of changes in nutrition (fertilizers) on growth, (4) nutrient cycling including carbon, (5) effects of improvements in genetics, and (6) effects of plantations on water yield. Such studies have been undertaken individually across a range of sites and it has been difficult to obtain an integrated understanding of the factors at a forest level and actually based on data rather than, say, modelled information. The current project aimed to address the range of the factors through a number of studies, as much of the data have been gathered for periods up to 40 years.

Some key reported outcomes relevant to this study have been:

- There are differences in productivity between rotations, and part of the difference can be explained but causative effects probably vary with site type (Long 1997, Squire *et al.* 1985, Evans 2005, O'Herir and Nambiar 2010). The O'Herir and Nambiar (2010) study is the most comprehensive at a management level and is related to sandy soils which represent about 17% of the Australian radiata pine estate (Turner *et al.* 2001) and results could vary on higher clay or sesquioxide rich soils.

- Relationships between soils and productivity have been developed which allow some identification of limiting factors to be undertaken (for example, Truman and Humphreys 1985).

- Plantations (trees and management) have an effect on soil properties (for example, Turner and Lambert 1988, Smith *et al.* 1994, Hopmans and Elms 2009) including residual effects of fertilizers (Turner *et al.* 2002) The magnitude and type of effect relate to site type and management but the effect of such changes on long term productivity is not consistently known.

- The effects of nutrient removals in harvesting are a critical factor in long term productivity estimation in plantations systems. While estimates of nutrient removals in harvesting from radiata pine stands have been made (Birk 1993), knowledge of impacts on productivity is limited (Turner and Lambert 2011).

- There have been genetic improvements in radiata pine, especially over the last 20 years as demonstrated in extensive trials (Johnson 1991, Carson *et al.* 1999, 2004). A question to be addressed is the extent to which these gains are realised in routine plantings. Are the genetic gains not being recognised because of offsets in the changes in productive capacity?

- Plantation management affects water yields from catchments and there has been analysis of this issue (for example, Major *et al.* 1998). Longer term studies in relation to radiata pine plantations are limited and data have been extrapolated. Lidsdale provides a situation with long records on a number of gauged catchments together with baseline catchments in native forest (Bell and Gatenby 1969, Putahena and Cordery 2000). Many of the analyses use a standard figure for crown cover as the effect of vegetation and hence do not include the relationship between actual forest productivity and water use and the consequent effects on runoff. Few estimates of water use efficiency have been undertaken at the field level.

Section 3. Lidsdale Forest - Site Details and Structure of the Study

Lidsdale State Forest (Latitude 33°24’ S and Longitude 150°00’ E) is located on the Great Western Highway about 130 km northwest of Sydney. The elevation is about 920 to 985 m asl. Mean annual rainfall averages 875 mm (40 years of records) and this is evenly distributed throughout the year (Figure 1). Mean minimum temperature is -0.8°C in July and mean maximum is 22.6°C in February. The soils are yellow Kurosols (Isbell 2002) derived from Permian conglomerate and Devonian shale and give rise to nutritionally poor, deeply weathered duplex soil with a generally impermeable B horizon (P.J. Ryan *pers. comm.*).

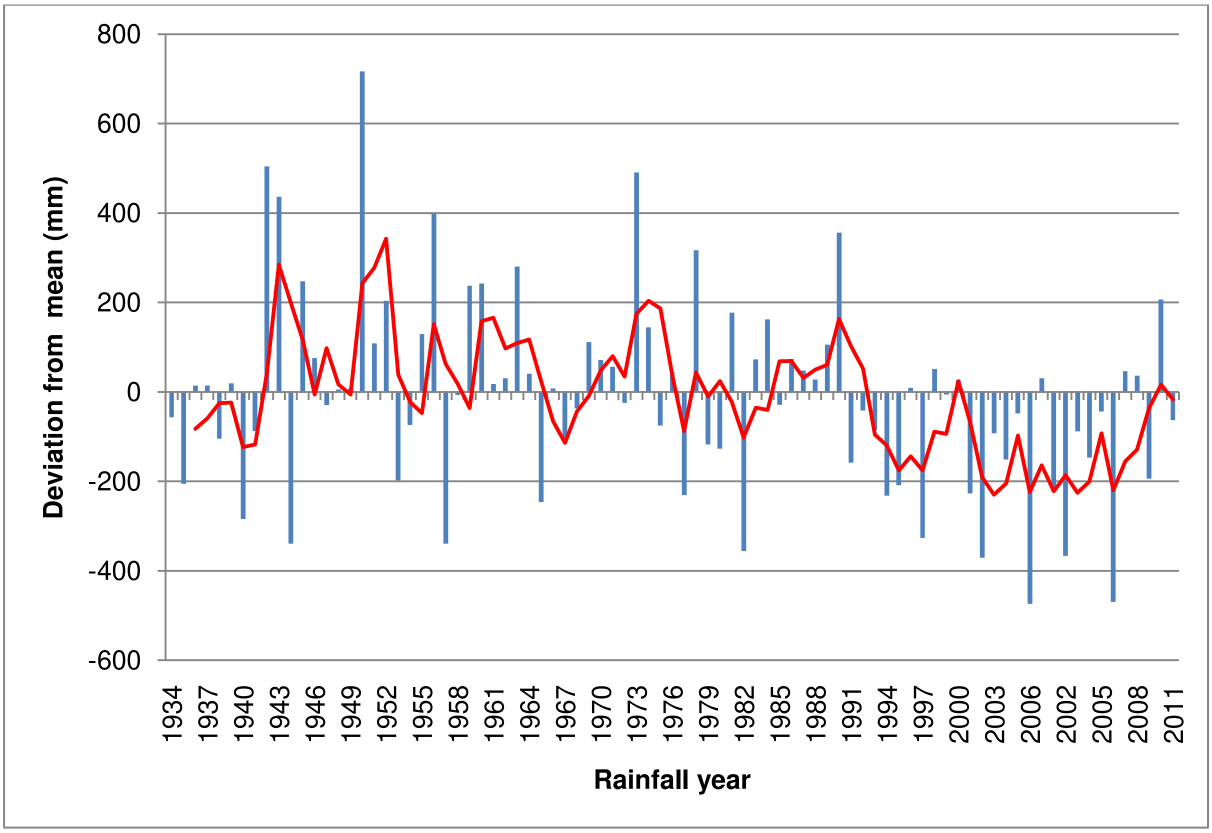

***Figure 1**. Rainfall deviations from mean and three year moving average of rainfall for Lidsdale State Forest.*

The natural vegetation has mixed species and is dry eucalypt woodland. The main species are *E. rossii*, *E. rubida*, *E. dives*, *E. mannifera and E. dalrympleana*. Tree ring analyses indicated that most trees appeared to have regenerated after 1918 and that prior to that, the area had been cleared for farming, grazing and fuel. Planting of *Pinus* species commenced in 1920 onto essentially cleared areas, or areas with scattered trees (Black 1948). Soil preparation involved surface cultivation on flatter areas or hand preparation on steeper country. Calcium was relatively low and exchangeable aluminium was high (Table 1).

Areas within the forest but not planted were either retained as cleared land or allowed to regenerate back to native tree species. The plantation was re-established to the second rotation and currently to the third rotation. The areas of the original first rotation plantations are presented in Table 2 together with replanting dates and the gross area of the plantation (Table 2).

Table 1. *Soil characteristics typical of the Lidsdale experimental area derived from Permian conglomerate.*

Depth (mm)	pH	N (%)	O.M[a] (%)	Total P (ppm)	Exchangeable (me%)					Clay (%)	Silt (%)
					Ca	Mg	K	Na	Al		
0-150	4.44	0.04	2.95	67	0.75	0.58	0.23	0.03	2.08	5	17
150-400	4.86	0.02	0.90	95	0.24	0.74	0.40	0.06	1.79	7	20
400-700	5.32	0.02	0.35	120	0.13	2.05	0.25	0.13	4.63	11	18
1100-1300	6.21	0.01	0.13	100	0.17	1.18	0.20	0.04	5.16	20	22

[a] *Organic Matter*

Table 2. *Lidsdale State Forest - plantation areas from 1920 to 1978. The gross area of the forest was 1,613 ha (from Forestry Commission of NSW, Bathurst Management Plan 1981).*

1R Age Class	Compartment No.	Area (ha)	2R Replant year	3R Replant year
1920	1	9	1960	1994
1921	2,3	24	1960	1994, 1998
1922	4	24	1960	1998
1923	5,6,7	49.4	1981	1998 (Cpt 5 not re planted)
1924	8,9	13	1978, 1982	
1925	10,11	45	1978, 1981	
1926	12,13,14	33	1981	
1927	15,16	28	1979	
1928	17a,18,19,20	38	1980	
1929	21,22,23,24	30	1979	
1930	17b,26,27,28	31	1980	
1931	25,29	40	1977	
1932	30,31	42	1977	
1933	32,33,34	42	1976	
1934	35,36,37,38	39	1958, 1978	
1935	39,40,41,42	57.4	1980	2000 (Cpt 42)
1944		6		
1978	Catchment 6	9		
Total		559.8		
Additional		21 (adjacent area)		
Grand-total		581		

A number of research projects and assessments have been undertaken within the forests. In addition to the productivity assessment from the 1930's, there were studies on soils, tree nutrition, productivity and hydrology some of which were commenced in the early 1960's. The data were used as the basis for the present research which was planned as a series of sub-projects and reported. Publications have been prepared based on these sub-projects.

These sub-projects are:

1. ***Published information***. Collation and analysis of published scientific information related to Lidsdale State Forest. The list of publications is available on request.

2. ***Native forest catchments***. Study of the long term productivity in the native forest catchments and nutrient cycling based on the intensive study commenced in 1977. The data were used to develop baselines for analysing some of the changes occurring in the pine plantations.

3. ***Pine catchments***. Study of the long term productivity in the pine plantations and nutrient cycling based on the intensive study commenced in 1977.

4. ***Fertilizer trials***. Analysis of long term fertilizer trials dating back to 1961 including residual effects of fertilizers into the subsequent rotation. The fertilizer trials were used to develop productivity baselines for fertilised and unfertilized stands.

5. ***Inter-rotational productivity and productive capacity***. Analysis of productivity, soils and nutrition in growth plots established in the first rotation and monitored into the second rotation. Soils sampled and analysed in the first rotation were re-sampled in the second rotation to evaluate changes in productive capacity.

6. ***Hydrology***. Analysis of published and available information from the eleven research catchments established in 1961. In addition, a review of forestry research has been undertaken (Appendix 1).

7. ***Integration of studies.*** **I**nteractions of components and analyses of the data.

Section 4. Pattern of Carbon and Nutrient Cycling in a Small Eucalyptus Forest Catchment, NSW

Turner and Lambert, M.J. (2014b). Patterns of carbon and nutrient cycling in a small Eucalyptus forest catchment, NSW. Aust. J. Bot. (In press).

Within Lidsdale, there have been three patterns of vegetation development, namely:

(1) Native forest cleared in the 19th Century and maintained as unimproved pasture (native species).

(2) Native forest cleared in the 19th Century, maintained as pasture until about 1918 and left to regenerate as native forest (mainly as coppice),

(3) Native forest cleared in the late 19th Century, maintained as pasture until about 1920 and progressively established as conifer plantation, mainly radiata pine.

Changes in carbon and nutrient distribution were analysed in a small catchment (Catchment 5) which fell into Catchment 2 (cleared and left to regenerate) to establish a baseline for comparison of the pine plantations.

The distribution and cycling of organic matter, carbon and nutrients were studied in a small, calibrated research catchment vegetated with regrowth eucalypt forest at Lidsdale State Forest, NSW. The catchment was used as a benchmark to study changes in the adjacent catchments planted to radiata pine. The catchment was studied in detail in 1977-1981 when the re-growth forest was approximately 64-years-old) with a repeat sampling and analysis in 2011-2012 (forest approximately 91-years-old). The soils are generally infertile as the example in Table 1 indicates. The natural vegetation is mixed species, dry *Eucalyptus* woodland where the main species are *E. rossii*, *E. rubida*, *E. dives*, *E. mannifera* and *E. dalrympleana*. The catchment was stratified according to land units and permanent plots were established for tree measurements and sampling, soil and litter sampling and litterfall estimation within strata. Biomass equations for each species were developed using trees adjacent to the catchment and used to estimate standing biomass and productivity. By applying nutrient concentrations of each component, the nutrient distributions, losses and uptake were estimated. The species varied in nutrient concentrations and in the ratios of nutrients (for example Figure 1) and these affected the distribution of nutrients and subsequent changes due to stand development.

The estimate in 1977 of the mean weighted average of the carbon content in Catchment 1 to a soil depth of 1 metre was 113.2 tonne C/ha of which 43.3% was in the vegetation and litter. In 2011, the total estimate had increased to 149.6 tonne C/ha with 55.1% in the vegetation and litter, an accretion rate of 1.1 tonne C/ha/y over the sampling period. In one of the strata, a significant part of the vegetation increase was as a result of radiata pine in-growth. The mean weighted average of nitrogen in 1977 was 3,900 kg/ha to 1 m depth of which 4.7% was in the vegetation and litter and this had increased to 4,188 kg N/ha in 2011 of which 6.7% was in vegetation and litter. There was an apparent increase of 8.5 kg N/ha/yr between 1977 and 2011. The phosphorus budget, using soil available phosphorus, indicated there was a total of 25.6 kg P/ha to 1 m depth in 1977 of which 45.8% was in the litter plus vegetation and this total had increased to 33.0 kg P/ha of which 57.1% was in litter and vegetation. This apparent increase was ascribed to transformation of phosphorus from less available forms (such as aluminium bound phosphorus) in the soil. When soil total phosphorus was estimated, there was 1,486 kg P/ha of which 0.8% was in the vegetation and litter.

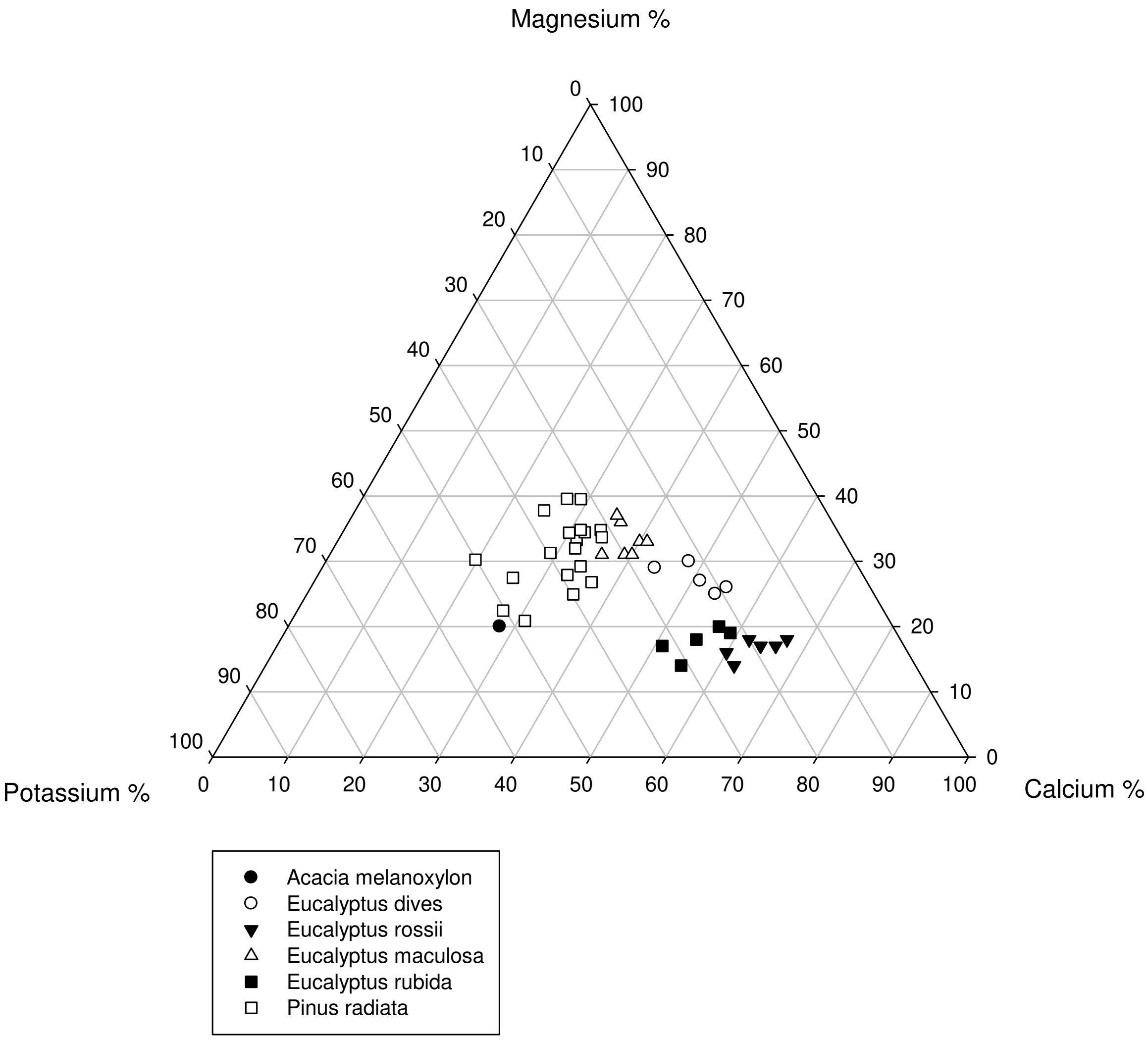

Figure 2. *Ratios of calcium, magnesium and potassium in the foliage of the species in Catchment 5.*

The estimate of calcium in 1977 was 1,163 kg Ca/ha (the estimate was based on exchangeable calcium) of which 51% was in vegetation and litter, and this had increased to 59% in 2011. The potassium was 1,066 kg K/ha of which 13.9% was in vegetation and litter and in 2011 this was 21%. There were similar estimates for magnesium where the mean weighted quantity in 1977 was 624 kg Mg/ha.

The turnover of nutrients was estimated including litterfall and throughfall together with increment increases which have been used to estimate annual uptake quantities. The inputs of nutrients in rainfall and the runoff outputs for the commencement of the study were also determined. The overall pattern showed long term transfers within nutrient pools, mainly from the soil to vegetation and in the case of calcium, shifts from deeper in the soil profile. The losses from the system (in runoff water) appear to be related to losses from bedrock weathering and deeper horizons in the soil. As the rooting depth over much of the catchment is limited, most of the nutrient cycling in the system is related to the vegetation and upper horizons of the soil. Considering the rainfall and the nutrients within the system, and using other forest types as a benchmark, it was expected this site would support a much more productive forest and the limitation appears to be due to restrictions in rooting depth as a result of high strength B horizon in conjunction with low nutrients.

Section 5. Long Term Changes in Nutrients within two small Radiata Pine Catchments

Turner, J. and Lambert, M.J. (2014c). Long term nutrient dynamics with two small radiata pine catchments. For. Ecol. Manage. (In press).

The changes in the distribution of organic matter and nutrients over a 34-year period were measured in two small catchments planted to radiata pine in NSW. The sites had relatively low productivity mainly because of the low phosphorus status. One catchment was cleared of native *Eucalyptus* regrowth and paired with Catchment 5 from the study in Section 4, approximately 60-years-old, and planted to pine while the other had mature pine plantation which was cleared and replanted to pine. Both catchments were part of paired catchment hydrological studies. Plots were established prior to clearing, measured and sampled and then the same plots were re-established after replanting and sampled and analysed using the same methodologies. At time of clearing, the eucalypt regrowth had an aboveground biomass of 104.5 ±33.9 tonne/ha and the mature pine (42-years-old) was 139±33.2 tonne/ha. In 1978-80, the aboveground net primary productivity was estimated as 9.99 tonne/ha/yr of which 29% was replacement compared with the adjacent native forest (Catchment 5) where the aboveground NPP was estimated at 6.76-7.37 tonne/ha/yr of which 68-78% was replacement. Nutrient distribution and turnover were assessed for the catchments as was water use.

Section 6. Analysing Inter-rotational Productivity in a New South Wales Radiata Pine Plantation

Turner, J. and Lambert, M.J. (2013). Analysing inter-rotational productivity and nutrition in a New South Wales radiata pine plantation. New Forests 44: 785-798.

One objective of forest management is to maintain long term productivity of forests. This is expressed in a number of ways but includes the concept that the supply of products from the forest area will be maintained in the long term (multi-rotations). The concepts related to sustainability are interpreted differently in native forests (such as with selection logging) and fixed rotation-length plantations. There are a number of factors in plantations affecting productivity and over the long term, managers need to be able to identify how they are changing and hence be able to intervene when appropriate. One approach is to consider that the productivity of the second (or subsequent rotation) will equal:

Productivity of first (prior) rotation x f [environment: productive capacity: genetics: management].

While these factors are interactive, it is not proposed that they are additive or multiplicative only that each has an impact. Aspects of the individual factors include:

Environment. Environmental factors affecting productivity include rainfall, rainfall regime, temperature and other factors. The relationship between environmental factors and plantation productivity needs to be considered on a site basis.

Productive capacity. Productive capacity relates to soil factors, primarily nutrient availability and physical factors. Three key aspects of the nutrient availability are nutrient removals in harvesting, nutrient losses in management (for example, burning) and residual fertilizer effects while physical factors relate to effects such as compaction. These components need to be addressed individually (for example, see models relating productivity to site).

Genetics. It is expected with the tree breeding programs, the genetics of the plantation will change (improve) over time. The issue of the overall performance of the plantation in the first rotation may need to be considered and where found to be lacking, species should maybe be changed.

Management. The management inputs have short and long term impacts and include site preparation (including treatment of residues), weed control, fertilizer additions throughout the rotation and density of planting.

Comparisons of productive capacity and productivity at the plantation scale were undertaken for first and second rotations of *P. radiata* plantation on clay soils in NSW, Australia where rotation length was about 30 years. Over a rotation, in compartments where there were no significant additions of nutrients, there were small declines in productivity from the first to the second rotation while productivity increased in the third rotation usually due to changes in management practices (Figure 3). Plots on soils derived from two different parent materials were identified (Permian and Devonian). On sites treated with significant quantities of phosphate fertilizer (50 kg P/ha) in the second rotation, there were significant increases in the productivity of the second rotation with a residual effect on increased productivity into the third rotation. The early growth of the second rotation may be higher than that of the first rotation but it changes with age. Rotation length productivity appears to be related to the magnitude of soil nutrient pools. Phosphorus and nitrogen play a dominant role in the early developmental stages of plantation development while nutrients such as calcium, potassium and boron appear to be affecting long term growth even though the foliage levels are much higher than normally considered to be limiting growth. Most of the differences in productivity between rotations appear to be related to soil nutrient or management changes while potential genetic gains as estimated from experimental trials, are difficult to identify.

In the simplest analysis, if environmental factors did not differ significantly between rotations and also there were no major differences in management, and there were no residual fertilizer effects, then the major factors affecting the second rotation relative the first are productive capacity and genetics. Issues that arise include estimation of actual changes in productive capacity and determination whether genetic improvements identified at the research level, have been translated into the field. For example, if the productivity of the second rotation was measured and found to be the same as the first, and the genetic material was to have a 10% increase in yield, has it been achieved and is it masking a true 10% decrease in the productive capacity. For a critical analysis to be of value, we need to develop a simple analytical model in which the components can be quantified.

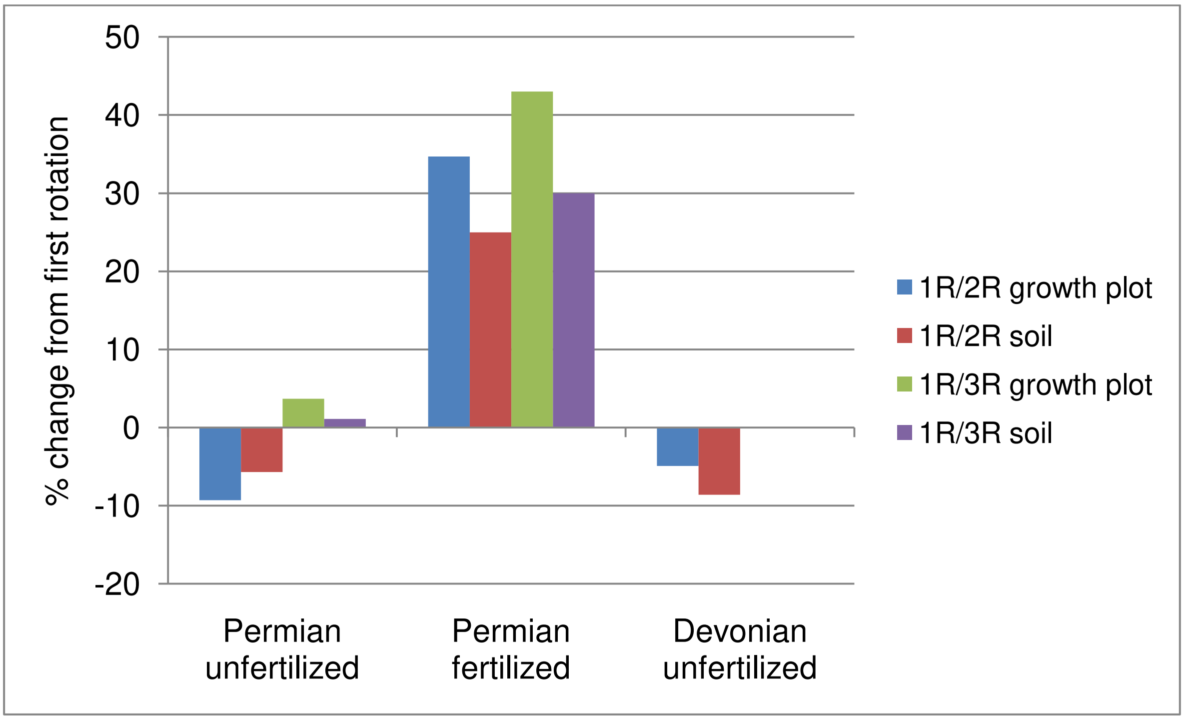

Figure 3. *Changes in growth relative to the first rotation at Lidsdale State Forest. The estimates from the growth plots are the second and third rotation compared with the first rotation and the soil estimates are predicted productivity (productive capacity) compared to the first rotation. 1R is the first rotation, 2R the second rotation and 3R the third rotation.*

Section 7. Long Term Growth Responses to Phosphatic Fertilizers in a Pinus radiata Plantation

Turner, J. and Lambert, M.J. (2014c). Long term responses to phosphatic fertilizers in a Pinus radiata plantation. For. Ecol. & Manage. (In press).

The effects of phosphatic fertilizer in trials on the growth and nutrients at different stages of stand development were studied in second rotation *Pinus radiata* sites at Lidsdale State Forest, NSW. The plantation had low nutrient status (particularly of phosphorus), root development was limited due to poor soil physical properties, and stand site quality was related to soil nutritional properties and foliage nutrient status. One established fertilizer trial showed high immediate growth responses to application of phosphorus or nitrogen/phosphorus fertilizer to individual trees at time of planting. Another large-scale trial showed long term responses to broadcast treatments of phosphorus or nitrogen/phosphorus at time of planting, however, it took several growing seasons for the trees to access the applied phosphorus. There was a delay in growth response when compared with spot applications. A further trial had later age applications of phosphorus, with and without nitrogen, and there were significant growth responses but these were related to the prior nutritional status of the stand which was in turn a function of the fertilizer history. The pattern of height growth was similar for both phosphate treatments and they differed from the control and the calcium-ammonium-nitrate (CAN) treatment (Figure 4). Volume growth over time was demonstrated for Block IV (Figure 5) showing similar patterns for both phosphate treatments. They were greater than the CAN treatment which in the later years was higher than the control. There was a diverging pattern between the CAN and the control up to 35 years of age.

Application of phosphorus or nitrogen/phosphorus after thinning gave significant increases in growth. Combining trial results and assuming treatments were additive, it was concluded that productivity could be increased from 8 m^3/ha/yr to about 16 m^3/ha/yr over 24 years (Figure 6). Growth responses have been compared with other radiata pine trials and some general principles are discussed.

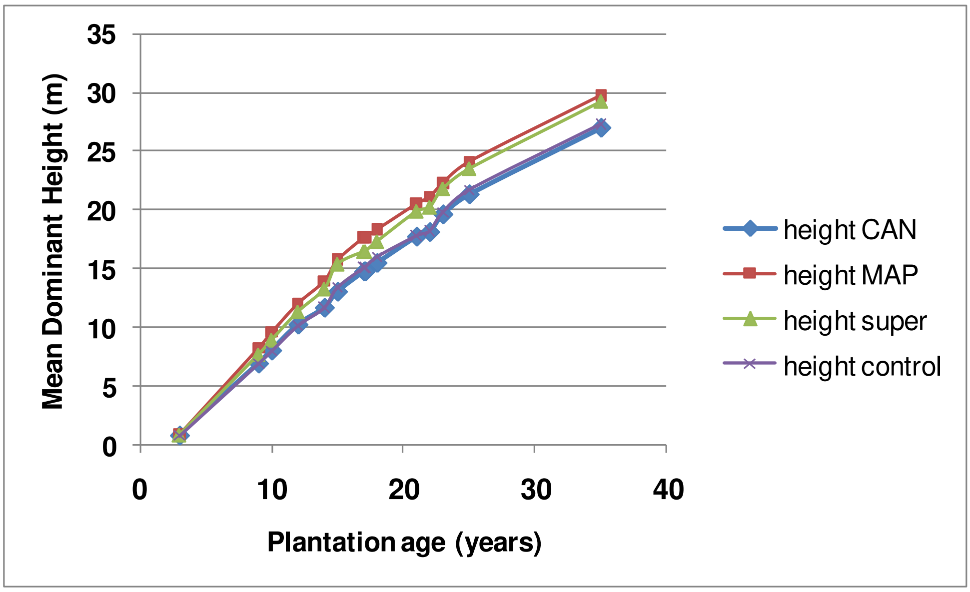

Figure 4. *Average height according to age for each treatment for the long term fertilizer trial.*

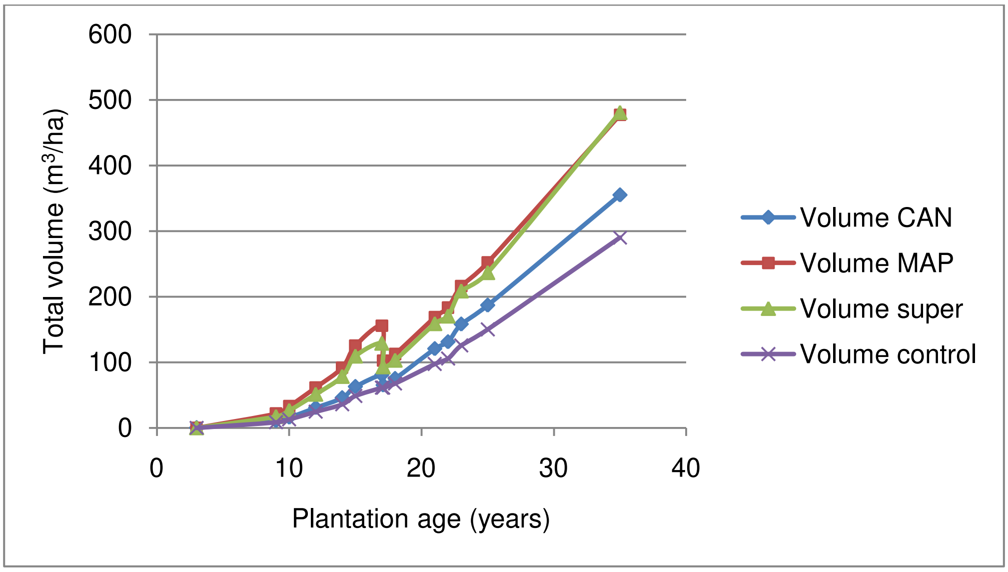

Figure 5. *Average volume and age for each treatment for the long term fertilizer trial.*

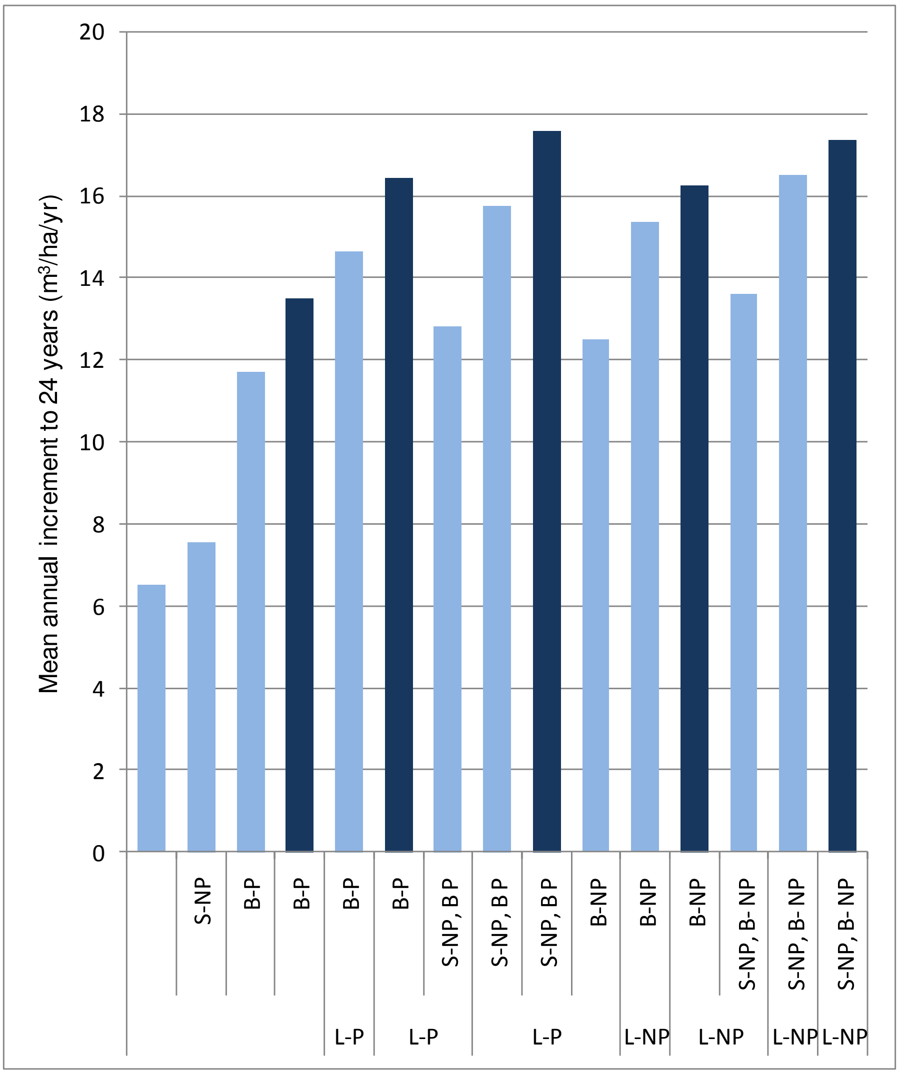

Figure 6. *The integrated mean annual increment volume using different fertilizer strategies. S-NP is spot applied establishment fertilizer. B-P and B-NP are broadcast superphosphate or mono-ammonium phosphate respectively. L-P or L-NP is later age broadcast application of superphosphate or NP fertilizers. The dark shaded columns are post thinning NP treatments.*

Section 8. Water Use in Plantations and Native Forests at Lidsdale State Forest

Use of water by forests and changes in production of water from forested catchments is a continuing issue, particularly as a result of forest management practices,. Plantations are often considered to be using excessive quantities of water and this may be attributed to species and management. A series of research catchments were established at Lidsdale to evaluate the impact of pine plantations of water yield. The available data from these catchments are evaluated for quality and where suitable, used for analysis on water use. Eleven catchments were established in 1962/63 as a joint project by the Forestry Commission of NSW and the University of NSW, the objective being to examine the effects of exotic softwood afforestation and management on the components of the hydrological cycle and the overall water yield. The catchments were selected to be as representative as possible in average conditions within the study area at the time. Four pairs of small catchments (7- 14 ha in size) were to provide the main basis for studying the difference between the hydrological characteristics of native forest and pine forest. Catchments 1-4 carried mature stands of *P. radiata* and Catchments 5-8 carried mature native eucalypt woodland; each pine catchment was paired with a native forest c Additionally, there was one small catchment (No. 9 in 1961) carrying newly established *P. radiata*, one large catchment (No. 10) with mixed pine management and one large native woodland catchment (No. 11). The runoff was monitored by the School of Engineering at the University of NSW for over about 25 years. These data were analysed in the context of other studies (see Appendix 1).

The main data available from Lidsdale was from those catchments used in the 1978 nutrient cycling studies and presented in a number of reports and theses. That is, data were available from about 1962 to 1993 from Catchments 2, 3, 5 and 6. Catchment 3 was maintained as mature pine throughout the study period (planted 1935, clearfelled 1999), Catchment 2 was cleared of the 1935 pine age class in 1977 and planted in 1978, Catchment 5 was retained as the native forest which had regenerated from pasture about 1920 and Catchment 6 was cleared of the native forest in 1977 and planted as first rotation pine in 1978. Catchments 2 and 3 were on Devonian sediments while Catchments 5 and 6 were mainly on Permian conglomerate.

The original details of the catchments plus reported information from early studies are presented in Table 2. The early analyses (Bell and Gatenby 1969) did not show a consistent pattern of differences in runoff between pine and eucalypt catchments. Catchment 9 (young pine) had higher runoff probably because parts had been cleared and also had reduced transpiration and interception. Later studies on two or three catchments reported by Pilgrim *et al.* (1974) indicated that the eucalypt catchment (Catchment 5) had higher runoff than the mature pine (Catchments 1 and 2). These studies had the problem that Catchment 5 was on different geology to Catchments 1 and 2. The differences in studies of Smith *et al.* (1974) were mainly as a result of interception rather than evapotranspiration differences (Table 3)

The clearing of Catchment 6 and planting to pine provides information on the longer term effects on hydrology of first rotation establishment on a previous native forest site. The annual rainfall and runoff for the native forest Catchment 5 (Figure 7) shows a very high degree of variability but over the record period rainfall has been about 752 mm and runoff about 99 mm or 13% of rainfall. This catchment is used as a baseline catchment for comparison with other catchments where vegetation changes have occurred.

***Table 3**. Summary data for the 11 Lidsdale catchments based on original analysis and catchment pairings (Bell and Gatenby 1969) and reported information.* *'Perm' is Permian geology and 'Dev' is Devonian.*

	Catchment No.										
	1	***5***	***2***	***6***	***3***	***7***	***4***	***8***	***9***	***10***	***11***
Vegetation (1963-64)	Pine	Euc.	Pine	Euc.	Pine	Euc.	Pine	Euc.	Pine	Pine	Euc.
Pine established	1935		1935		1935		1935		1960		Mixed
Stand in 1977	43	Mature	43	Mature	43	Mature	43	Mature	17	Mixed	Mature
Aspect	SW	SSW	S	W	NNE	NNW	NNW	NE	SE	E	SE
Geology (%)	95 Dev.	95 Perm.	85 Dev.	95 Perm.	100 Dev.	100 Dev.	100 Dev.	70 Perm.	100 Perm.	60 Perm.	70 Dev.
Mean Slope (º)	20	13	15	12	17	15	12	17	13	10	13
Changes in vegetation (1963-77)	Thinned 1970	Nil	Thinned 1974	Nil	Thinned 1970	Nil	Thinned 1970 Cleared 1974	Nil	Nil part Cleared	Thinned	Nil
Changes since 1977	Cleared 1978 Regenerated	Nil	Cleared 1978 Burnt Planted	Cleared 1978 Burnt Planted	Cleared 1998 Replanted	Nil	Nil	Nil	Nil	Mixed	Nil
Area (ha)	5.46	7.28	12.86	8.95	**9.71**	4.21	7.77	6.07	24.28	307.5	97.1
Bell and Gatenby (1969) annualised											
<u>1964</u>											
Rainfall (mm)	811	836	820	841	811	815	833	776	831	825	793
Runoff (mm)	219	275	208	281	269	220	207	182	314		
Difference (mm)	592	561	612	560	542	595	626	594	517		
% runoff	27.0	32.8	25.4	33.4	33.1	27.0	24.8	23.5	37.8		
<u>1965</u>											
Rainfall (mm)	503	499	500	500	503	493	494	499	506	502	474
Runoff (mm)	8.9	22.6	9.9	24.4	22.9	21.1	3.8	10.2	32.8		
Difference (mm)	494.1	476.4	490.1	475.6	480.1	471.9	490.2	488.8	473.2		
% runoff	1.8	4.5	1.9	4.9	4.6	4.3	0.8	2.0	6.6		
N.B. Area adjusted runoff	255	216	212	195	183						
Records 10/68 to 4/71 on per annum basis (Smith *et al.* 1974, adjusted by Pilgrim *et al.* 1974)											
Rainfall (mm)			871	895							
Interception (mm)			163	95							
Throughfall (mm)			708	800							
Runoff (mm)			72	127							
Soil moisture change (mm)			+9	+35							
Evapotranspiration (mm)			627	638							
% runoff			8.29	14.2							
Records 1974 to 1976 on annual basis (Pilgrim *et al.* 1982)											
Rainfall (mm)	842			870							
Interception (mm)	183			99							
Net throughfall	659			771							
Runoff (mm)	190			269							
Soil change (mm)	-3			1							
Evapotranspiration	472			501							
% runoff	22			30.9							
Records March 1978 to March 1981 on annual basis (Pilgrim *et al.* 1974)											
Rainfall (mm)	688	750		750							
Interception (mm)	88										
Net throughfall		662									
Runoff (mm)	123	103		162							
Soil change (mm)	-2	-15		-15							
Evapotranspiration	567	574		603							
% runoff	17.9	13.7		21.6							

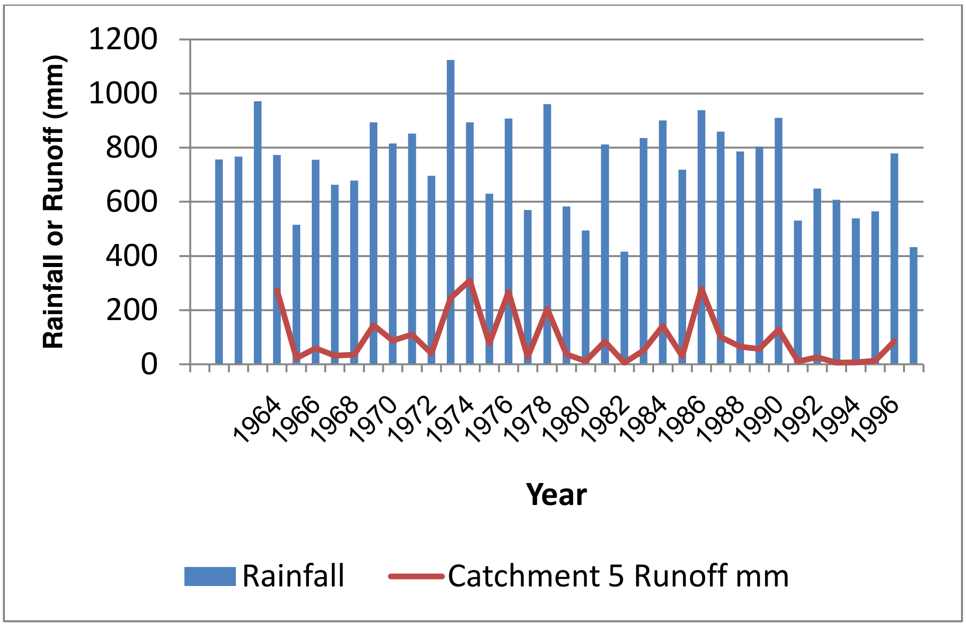

Figure 7. Annual *rainfall and runoff in Catchment 5 where the vegetation is native forest.*

Putuhena and Cordery (2000) reported on the runoff patterns for Catchment 6 in relation to Catchment 5 before and after the catchment was cleared for pine plantation establishment in 1978 and their results have been reported with additional years added. There was a significant increase in runoff immediately after clearing when interception and evapotranspiration were removed (there would be evaporation from the soil surface but not estimated), this amounting to nearly 200 mm in the first year (Figure 8). After that time, the increase in runoff declined and after the age where the plantation reached crown closure, the runoff was less than expected if the eucalypt vegetation had not been removed. The runoff was returning to the pattern prior to clearing and was expected to reach that in 1994-1995 as the growth rate of the plantation declined (this has been analysed and reported separately). The sum of the increased flows immediately after clearing (7 years later) was 479 mm and the sum of the deficit flows was 282 mm, that is, there was greater net runoff.

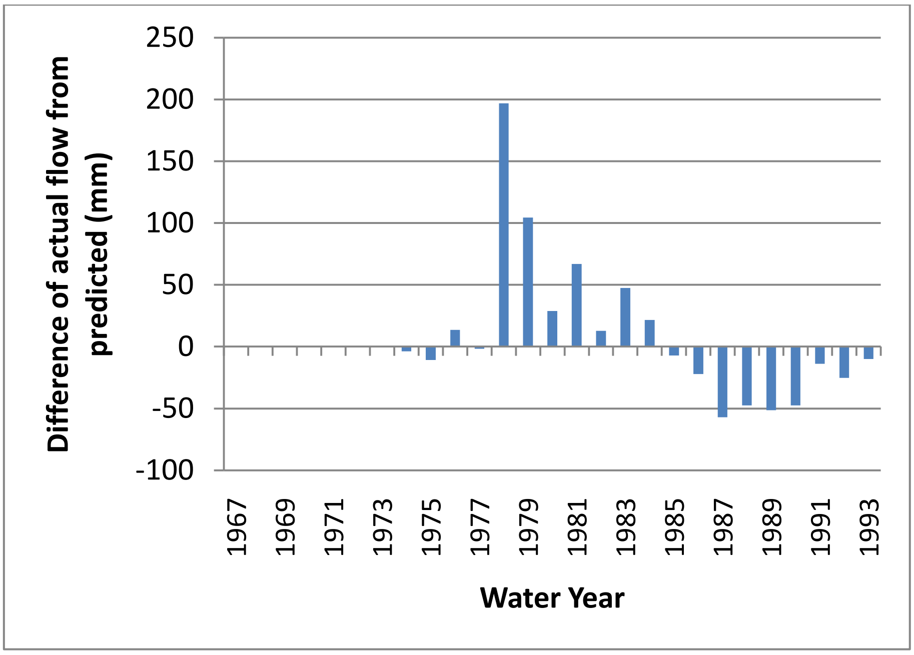

Figure 8*.* *Difference between actual flow and predicted flow for Catchment 6. Clearing took place in late 1977 and the planting to pine was in 1978. Predicted flow was modelled, based on the relationship to Catchment 5.*

The comparison of runoff from Catchments 2 and 3 represents the conversion of mature pine plantation to second rotation pine (Figure 9). The pattern of increased flow as a result of reduced interception and evapotranspiration followed by reducing runoff as evapotranspiration was similar to that for Catchment 6 where there was conversion of eucalypt to pine. However, the effect appears to be lower, probably as the baseline flows for the two comparisons were different. That is, the runoff from Catchment 3 (mature pine) was on average about 12% lower than that of the eucalypt catchment. The study from Red Hill (Major *et al*. 1998, Webb and Kathuria 2012) was included for comparison (Figure 9). The combined outcome of these studies shows that at time of establishment when evapotranspiration is low, there is increased water yield and this declines with stand development to an age which equates with maximum plantation production (near maximum period annual increment) after which runoff increases. The actual deviations depended on the baseline, that is, whether the comparison catchment was mature native forest, mature pine or pasture, these varying in evapotranspiration and interception. There are additional factors affecting variation including rainfall and any management undertaken (weed reduction or thinning) and while using a common baseline is not possible (differences in geology and other factors), the pattern between the studies appears to be consistent.

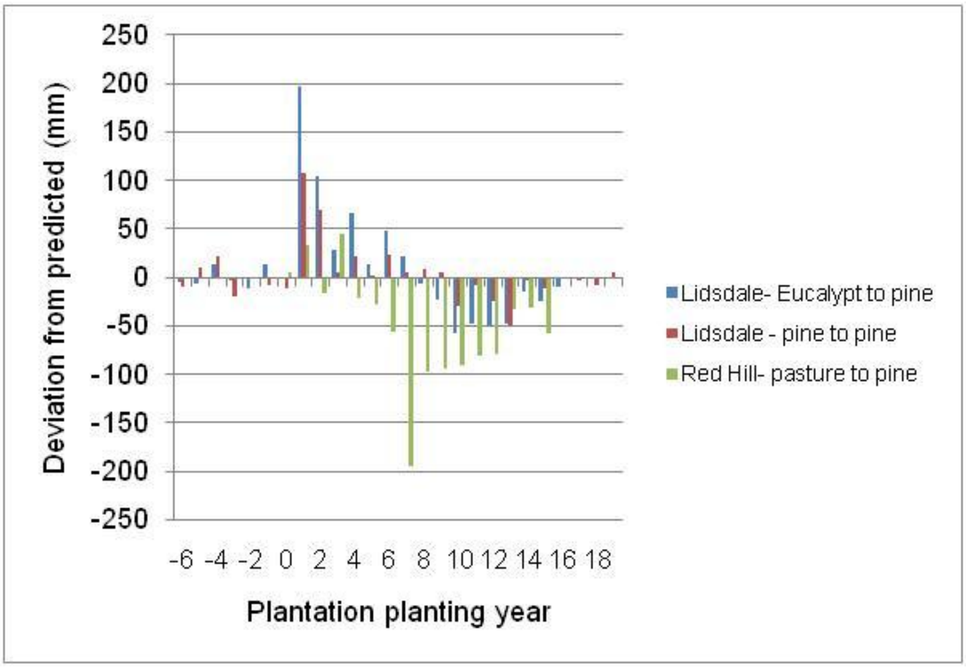

Figure 9. *Deviation from predicted runoff for a first rotation pine from eucalypts (eucalypt to pine), a second rotation plantation (pine to pine) and reported runoff deviation of converting pasture to pine at Red Hill.*

The use of small catchments shows the pattern of change when a large proportion of the catchment undergoes vegetation change in one year and there are no significant factors such as roads or marshy (unplanted) areas. However, this does not represent the typical situation for a larger catchment such as Catchment 10 where 9 age classes were contained in the 307 ha. The net planted area was 223.2 ha or 72.5% of the catchment. The rest comprised 10.5 ha of roads and tracks, 47.5 ha of areas unplanted and 26.3 ha unplanted or failed areas. The last of these were mainly areas within drainage lines on the Permian conglomerate. The diversified planting leads to more gradual changes over extended periods of time (Figure 10).

A number of estimates of nutrient losses in runoff have been undertaken. One of the estimates was for the year 1978 for five catchments after disturbance had occurred in three of them (Mackay 1982). A comparison of cation ratios in runoff water and rainfall inputs shows differences indicating runoff is probably more affected by the underlying geology than rainfall chemistry (Figure 11).

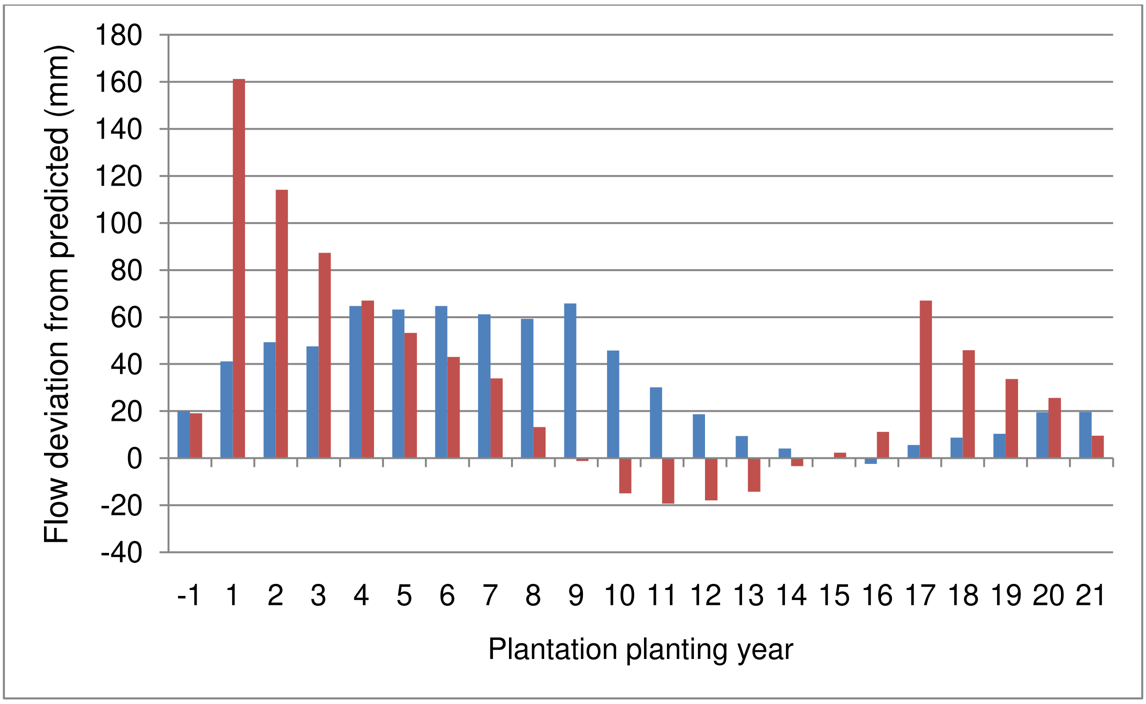

Figure10. *Deviations in estimated runoff for Catchment 10 (integrated catchment) showing the effect of planting an available area in one year (blue) and planting over several years (red). The rise in year 17 is the impact of first thinning.*

Table 11*.* *Nutrient losses 1/11/1977 to 31/10/1978. Rainfall inputs from Turner et al. (1996).*

Catchment	***Treatment***	***Runoff (mm)***	***N***	***P***	***Na***	***K***	***Ca***	***Mg***	***SO4-S***
					(kg/ha/yr)				
Rainfall inputs		1001	0.89	0.11	2.93	5.99	0.82	0.55	3.75
No.1.	Clearfell 1978 – regen.	277			1.79	0.85	1.03	0.82	2.30
No. 2.	Clearfell 1977 – planted	430			2.13	1.54	1.10	0.88	5.10
No. 3.	Mature pine	253			1.68	1.01	1.01	0.53	2.45
No. 5.	Mature eucalypt	257	0.14	0.016	0.88	0.56	0.38	0.57	4.11
No. 6.	IR pine (1977)	297			2.54	1.87	1.97	2.70	15.4

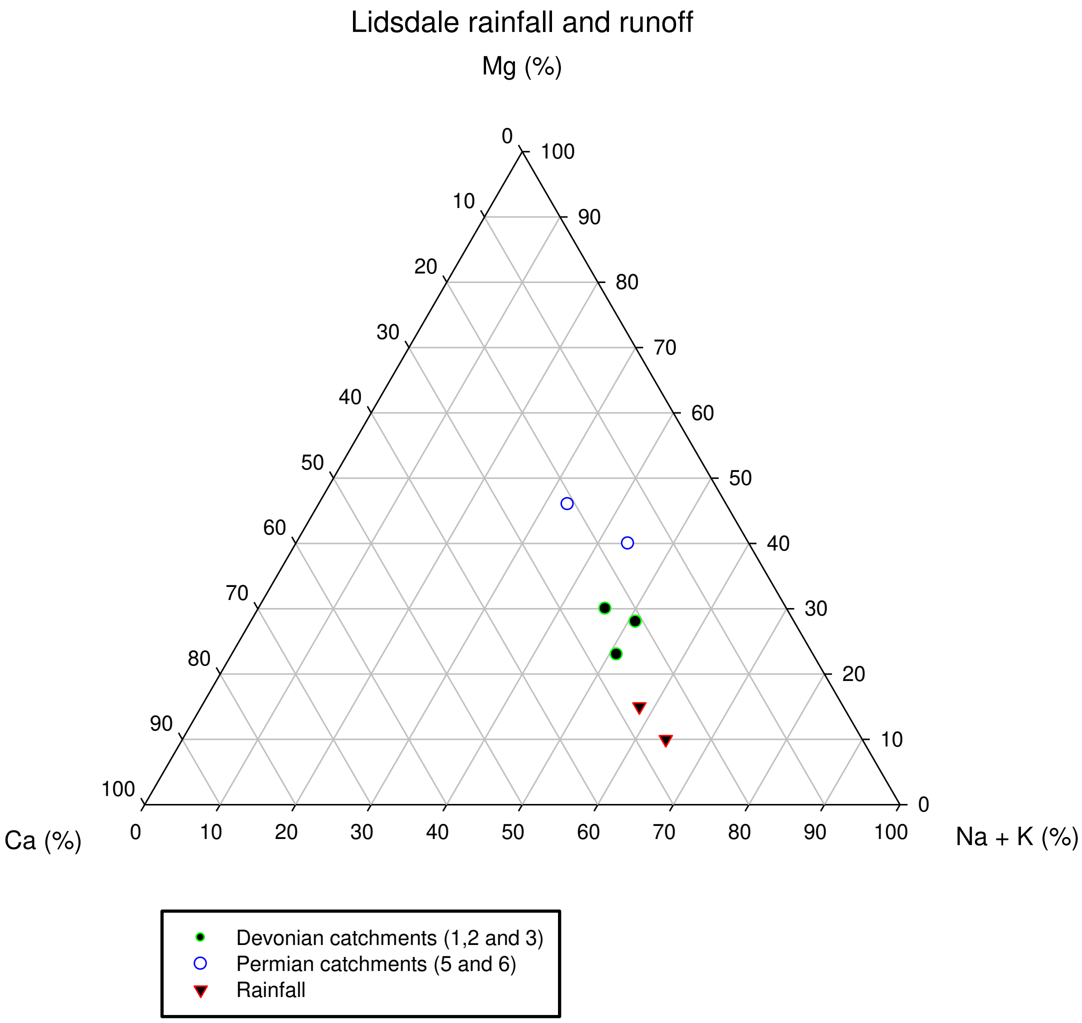

Figure *11.* *Cation ratios in rainfall and runoff from Lidsdale catchments.*

An analysis of Water Use Efficiency (WUE) relevant to Australian conditions at the forest stand level was undertaken using the information from the catchments plus published data (see Turner and Lambert 2010a). WUE of different forest types at the forest stand level were analysed using plot and catchment data. WUE was calculated as aboveground NPP/ET (g/litre), that is, Net Primary Productivity divided by stand Evapotranspiration. No differences in WUE could be identified between forest types (specifically radiata pine and eucalypts), however, WUE was significantly related to stand age and this is the primary factor leading to differences in reported comparisons (Figure 12). A second factor related to WUE was organic matter replacement (litterfall/NPP) which is also related to age, that is, WUE declines as the proportion of litterfall increases in total productivity. If WUE was defined as net organic matter accumulation divided by precipitation minus runoff, there were differences between forest types and a large part of this is as a result of interception differences. Differences reported in overall water use between forest types are considered to be a result of differences in interception and current productivity rather than WUE.

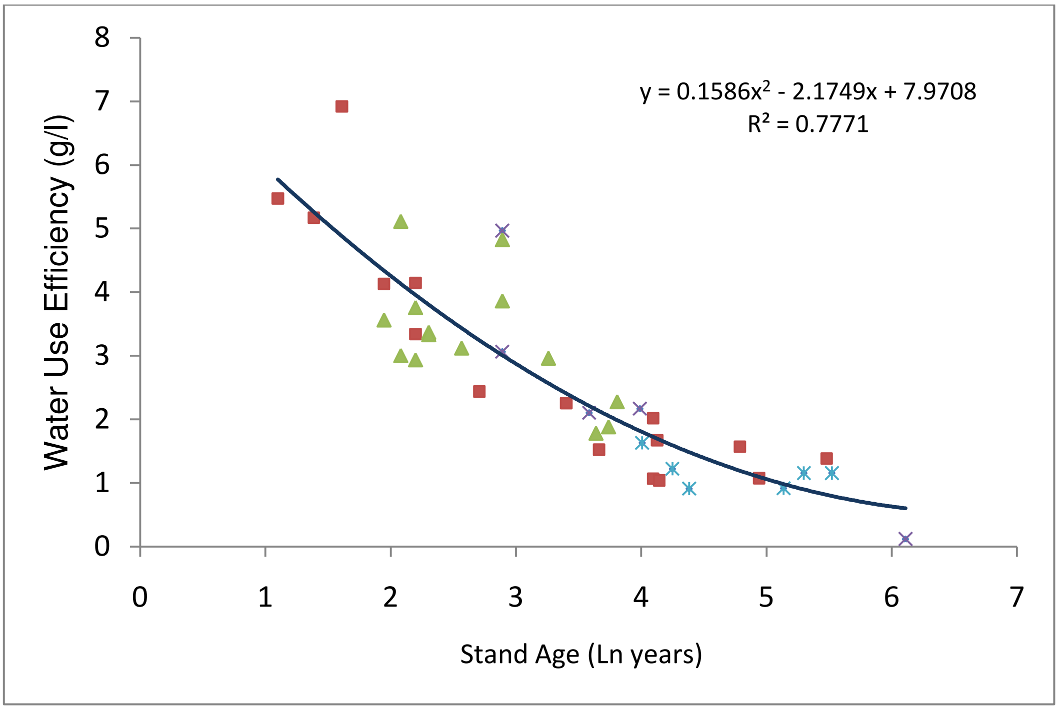

Figure 12. *Stand age and Water Use Efficiency. Eucalypt forests (native or plantation) are shown as squares, pine plantations are triangles, other conifers are crosses and other forest types are hatched crosses.*

Integration

The Lidsdale study evaluated long term changes in growth and nutrients in pine plantations and adjacent native forest. The study emphasised problems with long term studies. The loss of data over time was especially critical. Further, short term patterns and changes do not necessarily represent the long term changes, and in practice, the short term studies may be misleading for issues such as sustainability.

The productivity of the second rotation, where fertilizers have not been applied in significant quantities, is lower than in the first rotation. This appears to be as a result of nutrient removals in harvesting, especially for calcium, potassium and boron. Where significant quantities of fertilizer are applied (in this case phosphatic fertilizer), productivity is significantly increased in the second rotation and there are residual effects (that is, higher productivity) into the third rotation. However, based on fertilizer trials, the increased productivity on the fertilized areas was not as large as expected. While fertilizer applications are usually considered and assessed individually (for example, establishment, early age, or post thinning), treatments are both cumulative and interactive and hence whole of rotation nutrient management planning should be undertaken to optimise the utilisation of nutrients. With appropriate rotation length, it should be possible to manage nutrients to further increase plantation productivity in future rotations.

Critically, in the development stages of the rotation when crown mass is being developed or after thinning when crowns are re-developing, nitrogen and phosphorus are important, however, when the production of the whole rotation is considered, nutrients such as calcium and potassium are important. This shows up in a number of ways, particularly in the relationship between soil nutrients and productivity. Comparisons with other sites indicate that soil-based site types may be used to identify the susceptibly of sites to respond to either nutrient removals or nutrient additions. This should be incorporated in a site classification system used for site specific management.

The studies were used to evaluate long term changes in carbon and nitrogen distribution. Carbon accumulates in biomass and soil over time and the accumulation rates are much higher in the plantations than in the native forest. The rate of soil carbon accumulation is related to forest net primary production and consequently, increases in productivity as a result of treatments such as fertilizer application will increase the rate of carbon accumulation.

The studies showed that removal of vegetation and the consequent reduction in evapotranspiration increases runoff. Development of forest stands, in this case plantations, uses water and consequently runoff declines and when productivity decreases, runoff increases. The highest runoff is from pasture. To minimise the long term patterns of decreased and increased runoff, the pattern of harvesting (thinning and clearcut) and re-establishment should be planned so only a proportion of larger catchments is affected in any year. Productivity and carbon accumulation utilises water and increased accretion of carbon will require additional water utilisation. Planning and implementing systems to account for the interaction of productivity, carbon accretion and water use requires further analysis.

Acknowledgements

We wish to acknowledge assistance with the project by FWPA and the NSW Forestry Corporation and Dr David Flinn for comments on draft papers.

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Appendix No. 1

August 2013

REVIEW OF HYDROLOGY PUBLICATIONS
RELEVANT TO
SOUTHEASTERN AUSTRALIAN FORESTRY

Prepared by

John Turner and Marcia Lambert

Forsci Pty Ltd

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Abstract

Forests are important in the production of water and in management of environmental problems such as salinity. Disturbance of the vegetative cover and the soil affects the runoff in streamwater and may include harvesting or clearing of native forests, replacement of native forest with plantation, replacement of pasture with plantation, or harvesting within plantations. A number of studies have been undertaken in this regard and general results include the following:

- *Removal of trees in native forests, either by harvesting or wildfire, produces a rise in water yield including an increase in stormflow runoff peaks. The rise in water yield is proportional to the percentage of the area of the forest removed and is most pronounced one to three years after disturbance.*
- *An increase in forest cover leads to a decrease in streamflow and this is proportional to the increase in the area forested.*
- *If less than 20% of a catchment area is disturbed (clearing or addition of forest), changes in water yield are difficult to detect.*
- *The level of change in water yield in forests is generally related to the mean annual rainfall. The greater the rainfall, the greater the magnitude of the change.*
- *Native forests generally use more water than grasslands, the result being that grassland catchments have higher flow, with higher storm peaks, than equivalent catchments in native forests.*
- *The higher water use is attributed to increased canopy interception, greater rooting depth and the higher annual productivity of native forest compared with grassland.*
- *Plantation studies in Australia are almost entirely undertaken in pine plantations and there is little information on hardwood plantations.*
- *At time of clearing for plantations, there is increased streamflow (reduced evapotranspiration) followed by a period of increasing water use and commensurate reduction in flow as the plantation develops. This appears to reach a stable level at some time after crown closure.*
- *Water use in pine plantations is greater than in grasslands and native forests. The major difference between pine plantations and native forests appears to be related to canopy interception.*
- *Thinning of plantations and native forests increases water yield.*

Catchment studies need to be long term to allow for suitable calibration and pre-treatment monitoring. The number of studies that have been undertaken is limited in extent and hence changes have been predicted using modelling systems. Any analysis needs to include actual regulations and Codes which are related to land uses which restrict planting in key areas (for example, creekside reserves, etc).

Most studies are undertaken in small catchments and in the upper part of a catchment and these tend to be highly responsive, more-so than is typical of larger catchments. The relevance of extrapolation from small research catchments to larger catchments is a significant issue. The water yield in a larger catchment will be affected by the proportion of the total area under plantation, the distribution of the plantings, the age class distribution and the silvicultural treatments.

Water quality is an important issue in all forestry operations. When compared across land uses, forests produce the highest quality water. The main source of sediment in forest systems is identified as coming from roads and these needs to be managed carefully. Establishment of plantation on grassland areas will reduce sediment and nutrient loss.

Plantations have effects on salinity issues and these vary depending on where plantings are located in the landscape, the scale of the plantings and the rainfall regime. The main factor affecting salinity is a lowering of the watertable and the rate of such a change is dependent on the productivity of the plantings. Impacts can be very rapid with significant watertable and salinity reductions occurring within a decade.

1. Introduction

Forests are not only important for the production of a range of products including wood and water, but also for amelioration of some environmental problems such as salinity (Goss 2000, Powell 2000). However, not all of the products or values can be maximised and hence understanding of the processes involved and planning to balance outcomes, is essential. The study of forest hydrology provides a scientific understanding of how water moves through forested ecosystems, both native and plantation. There has been considerable and longstanding interest in the effects of forests and forest management on water yield and water quality (for example, McArthur 1964, McArthur and Cheney 1964). Additionally, there needs to be an understanding of the impacts of natural and land use disturbance on water movement and also how they affect the quality of the water.

The procedure used by hydrologists to study the movement of water in the landscape is to determine the water balance using catchment experiments. Two basic forms of catchment experiments have been undertaken, namely:

- ***Single catchment studies*** where a single catchment is studied for a period of time, then treated or disturbed in some way, and any changes in the pattern of runoff then monitored.

- ***Paired catchment studies*** where two catchments are monitored for a period of time, after which one catchment is treated, and the change relative to the untreated catchment, is monitored (Best *et al.* 2003).

A number of such studies have been undertaken within Australia assessing effects within native forest catchments (for example, harvesting, fire, etc), or conversion of native forest to plantation, or comparison of plantation established on pasture sites with the pasture. There are many other catchment studies which have been undertaken in agricultural and grazing areas but these have not been considered in this review.

Within catchment areas or at a plot level, studies have been undertaken to determine the partitioning of incident water. They include studies on interception, throughfall, stemflow, evaporation, transpiration and movement of water within the soil profile. Together, the changes in the water balance can be determined with the use of the water balance equation of which one form is:

$$P = Et + Ei + Q + G + \Delta S$$

where:

P = *Precipitation*
Et = *Evapotranspiration*
Ei = *Interception loss*
Q = *Streamflow {quickflow (Qf) + baseflow (Qb)}*
G = *Change in groundwater storage*
ΔS = *Change in stored soil moisture.*

Basically, over a study period such as one year, where there is insignificant change in groundwater and soil water, the vegetation component (interception and evapotranspiration) is inversely correlated with streamflow. Therefore, for a given quantity of rainfall, when the evapotranspiration increases the runoff will decrease and *vice versa*.

Water quality is also a critical component of studies on forest hydrology. Water quality of undisturbed forest catchments is usually very high and mainly affected by an interaction between the forest type and the underlying geology. Forest management, as for any land use, will disturb the soil leading to short and long term changes in water quality. This may be addressed as changes in nutrient concentrations within streams or as total loadings (that is, the quantities of nutrients or sediments that are lost from a catchment). Changes in land use, such as the establishment of plantations on cleared and/or salinised land has the potential to lead to improvements in water quality through reduction of soil erosion and nutrient losses.

In any of the aspects of forest hydrology which are studied, there are significant variables such as rainfall variation over time, forest growth changes, and the levels of disturbance. To understand the changes and predict outcomes, a number of models have been developed. Such models have high value especially considering the long periods of time and the costs involved in maintaining catchment studies. While accepting the value of different models, the basic structure, assumptions and outputs of the various models have not been addressed in this review.

The present document outlines the readily available literature related to native and plantation forest hydrology together with some comments on the findings. It is not intended to be a critical review of all the literature but should serve as a source document. The focus has been on studies related to the water balance and has not addressed in detail, the methods of study and the relative value of individual methods.

2. Quantity of Runoff Water from Forests

The understanding of the effect of forestry operations on runoff in Australia has been greatly affected by hydrology research conducted in the United States. Early studies such as those at Hubbard Brook (Bormann and Likens 1979, Likens and Bormann 1980) or Coweeta (Swank *et al.* 1988, Hornbeck *et al.* 1993) provided understanding of patterns and also set a basis for the methodologies used in other areas. However, considering the variability reported from those studies, actual quantitative effects are difficult to extrapolate to Australian conditions. Based on a series of paired catchment studies, Stednick (1996) reviewed the effect of timber harvesting in US forests on water yield. In general, he found that changes in annual water yield from forest cover reduction (or catchment area harvested) of less than 20% could not be measured by streamflow measurement methods. Using hydrometric regions (regional units based on rainfall and temperature), it was suggested that harvesting 15% of an area would give a measurable increase in water yield in the Rocky Mountain Region compared with 50% in the Central Plains (there was considerable variation within each region). Principles of the methods were considered for determining return to pre-treatment conditions. Basically, the type of change in flow as a result of disturbance was consistent but the magnitude and timing varied according to the Region (that is, different environmental conditions). A review of using paired catchment to study effects of alterations in vegetation on runoff was undertaken by Brown et al (2005).

3. Native Forests, Effects and Comparisons with Grassland

In 1939, a wildfire burnt areas within the Melbourne Board of Works water supply catchments. The subsequent regrowth of the high quality mountain ash (*Eucalyptus regnans)* forests in some of the catchments led to significant reductions in water yields and they were studied in a number of projects (Langford 1976, Langford and O'Shaughnessy 1977a, b). Vertessy *et al.* (1998) summarised results of research and modeling and these are considered representative of results from forests in higher rainfall areas. In their introduction, they reviewed existing studies and indicated that:

- A reduction in forest cover produces a rise in water yield and a rise in stormflow runoff peaks. Conversely, when forest cover is increased, water yield and stormflow runoff peaks decrease (NB: *This is crown cover which may not be related to net primary productivity*).
- The rise or fall in water yield is proportional to the percentage of the area of forest added or removed.
- The extent of water yield changes brought about by changes in forest cover tends to increase with mean annual rainfall (based on Bosch and Hewlett 1982, Schofield 1996).
- Water yield changes are difficult to detect if less than 20% of the catchment is treated.
- Forests (based on native forests) use more water annually than grassland. Grassland catchments therefore have higher runoff and increased recharge (for example, Holmes and Sinclair 1986).

Vertessy *et al.* (1998) reported on earlier work in the mountain ash forests where the water yield from the ash forests was related to forest age (Langford 1976, Kuczera 1987, Vertessy et al. 1993, 1996). They found a relationship between mean annual streamflow and forest age (estimated up to 200 years) and key points were:

- The mean annual runoff from large catchments covered by pure mountain ash forest in an old growth state was approximately 1200 mm/year where the mean annual rainfall was 1800 mm/annum
- After burning and full regeneration of the mountain ash forests with young trees, the mean annual runoff reduced rapidly to 580 mm/year by 27 years of age.
- After 27 years of age, mean annual runoff slowly increased, returning to pre-disturbance levels, but took as long as 150 years to recover fully. (*Vertessy et al. (1998) considered that the problems with this model were its high error bands and difficulty of prediction*).

Vertessy *et al.* (1998) reported on a number of methods to quantitatively assess the different components of the water balance and applied these to mountain ash forests in Victoria. Components of the water balance for different aged stands are shown in Table 1. The analysis indicated that tree leaf area index was reducing with age while the understorey was developing over the period. Rainfall interception was significant and represented 22% of rainfall at 15 years of age and was estimated as 14% at 240 years. As vegetation water use declined, runoff increased and initially was as low as 460 mm rising to 880 mm or 49% of precipitation.

Table 1. *Estimates of water balance quantity for five different age classes of mountain ash forest (Haydon et al. 1996, Vertessy et al. 1998). (An annual rainfall of 1800 mm was assumed and each estimate has been rounded to the nearest 10 mm).*

	Stand age (years)				
Parameter	***15***	***30***	***60***	***120***	***240***
Overstorey LAI [a]	3.8	3.1	2.3	1.7	1.2
Understorey LAI [a]	0.4	1.1	1.8	2.3	2.4
Total LAI [a]	4.2	4.2	4.1	4.0	3.6
Overstorey sapwood area (m^2/ha)	10.6	8.1	6.2	4.7	3.6
Overstorey transpiration (mm)	760	580	440	340	260
Understorey transpiration (mm)	50	130	220	290	300
Rainfall interception (mm)	400	450	440	370	260
Soil/litter evaporation (mm)	130	120	120	110	100
Total evapotranspiration (mm)	1340	1280	1220	1110	920
Runoff (mm)	460	520	580	690	880

[a] *LAI = Leaf Area Index (m^2/m^2)*

A number of research programs involving small research catchments have been established in native forests in southeastern Australia. The Karuah Hydrology Research Project commenced in 1974/1975 and consists of eight small catchments in the Karuah catchment near Newcastle, NSW and was important as it represented moist old-growth forest. The initial cooperators on this project were State Forests of NSW, Metropolitan Water, the Hunter Valley District Water Board, the Water Resources Commission and the Soil Conservation Service. The catchments were calibrated and then harvesting was undertaken by State Forests of NSW. Following logging, water yields increased by 150-250 mm per year and the magnitude of the increase was proportional to the area of the catchment logged (between 29% and 79%) (Cornish 1993, 2001) and were in a comparable manner to results from North America reported by Stednik (1996). Where less than 20% of the area of the catchment had vegetation disturbance, there was no detectable increase. Water yield in all catchments started to decline 2-3 years after treatment as regrowth eucalypts developed and the rate of the decline was related to the level of tree regeneration stocking. This water yield decline exceeded 250 mm in the sixth year after logging in the catchment with the highest stocking of regrowth and the highest basal area, (that is, the highest net productivity). Water yields in this catchment declined to levels significantly below pre-logging levels and it was interpreted that regrowth evapotranspiration had begun to exceed that of the old-growth. A summary of the catchment treatments is shown in Table 2.

Table 2 *Areas of the catchments logged in the Karuah Hydrology Research Project (Cornish 1993). The main commercial species in order of presence were E. saligna, E. laevopinea, E. campanulata, E. quadrangulata and Lophostemon confertus. Treatments were carried out in 1983. The stocking and basal area were for regrowth or planted areas.*

Catchment Name	***Area (ha)***	***Treatment***	***Area treated (ha)***	***Proportion treated (%)***	***Stocking 9 years (stems/ha)***	***Basal area 9 years (m^2/ha)***
Crabapple	14.7	Control	0	0	0	0
Sassafras	25.2	Control	0	0	0	0
Barratta	36.4	Harvested	9.2	25.4	1100	8.4
Bollygum	15.1	Harvested	4.9	32.4	1600	12.8
Corkwood	41.1	Harvested, burnt	16.6	40.4	3500	12.7
Jackwood	12.5	Harvested, burnt	9.9	78.8	5200	16.6
Kokota	97.4	Harvested, burnt, planted to *E. laevopinea*	28.3	29.1	600	12.0
Coachwood	37.5	Harvested, burnt, planted to *E. laevopinea*	22.8	60.7	4000	28.4

A series of five catchments were established in 1977 by State Forests of New South Wales in the Eden Catchment Research Project within Yambulla State Forest. The forest type is dry eucalypt regrowth including *E. sieberi*. The catchments were treated, intentionally (by harvesting) and accidentally (by wildfire), at different times. A number of publications have been produced from the study and they provide basic information on forest hydrology within drier forests (Mackay *et al.* 1980, Mackay and Cornish 1982, Cornish and Binns 1987, Mackay and Robinson 1987, Turner *et al.* 1992).

After a severe wildfire in January 1979, the effects on the catchments were assessed (Mackay and Cornish 1982, Mackay *et al*. 1980). Pre-burn water yield and catchment responses were variable, depending on the storm rainfall and antecedent conditions. After the fire, diurnal fluctuations ceased (reduced vegetation), base flow increased (less transpiration), and peak runoff increased several fold in the burnt catchments compared with the control. Differences in runoff persisted for at least one year. Clearfelling in a burnt catchment after fire caused additional runoff and a significant increase in peak flows (that is, vegetation impacts were reduced further).

A second series of research catchments was established in 1984 in the Eden area in higher elevation forests within the Tantawanglo Creek Catchment. An initial study providing baseline information (Bek 1985) considered water quality variability within the existing larger creeks. The main reason for establishment of the research catchments was to address the effects of intensity of harvesting on water properties in higher elevation forests. Three catchments were involved, one maintained as a control, one with dispersed logging (removal of 12% of basal area) and one with more intensive integrated logging (removal of 47% of basal area). Wronski (1993) provided an assessment of the effect of harvesting on runoff from the research catchments. There were increased flows six months after harvesting ceased in the catchment which had undergone dispersed sawlog logging. Three years after harvesting, flows were still elevated and there was no indication of a decline in monthly flow rates to pre-logging levels. There was relatively minor regeneration because of limited site disturbance.

The catchment which had undergone more intensive integrated logging led to an immediate increase in runoff but this started to decline as regeneration increased. Within three years after logging, the cumulative total discharge from the catchment was less than expected if no logging had occurred. A revision of the work was carried out in 1997 (Lane and Mackay 1997). Over the whole observation period after logging, the light logging increased streamflow by 24% but the increase was only 3% for the same period in the more heavily logged catchment. The peak change was between 77 mm and 100 mm deviation (annual precipitation approx. 1100 mm). A large proportion of increased flows were derived from high magnitude/low frequency runoff events. The pattern of change is presented in Figure 1.

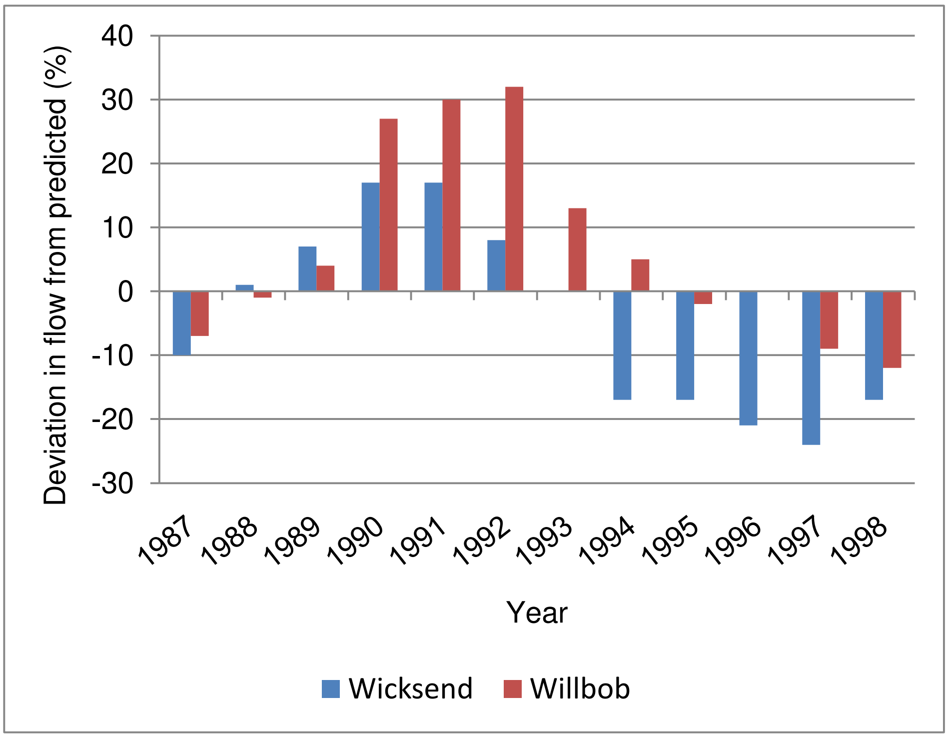

Figure 1. *Deviations in flow at Wicksend (more heavily harvested) and Willbob (less heavily) compared to control (Lane and Mackay 1998).*

Cornish (unpublished data) compared the effect of harvesting on streamflow for two years following harvesting in both the Yambulla and Tantawanglo projects. He reported on increases in flow from Tantawanglo in the first year after harvesting and increased flows in the second year in Yambulla, the first year having limited flows due to drought. The area logged (as opposed to basal area removed) was not detailed but it would appear that if applying the results from Karuah were applied to Yambulla, the changes in flow would have been over-estimated.

Burch *et al*. (1987) reported on the different hydrological behaviour of one catchment under dry native forest and another cleared and grazed for over 80 years at Puckapunyal, Victoria. The catchment study was initiated in 1981. The grassland catchments generated high peak stormflows and large discharge volumes irrespective of antecedent soil moisture conditions, whereas the forested catchment gave little runoff provided the antecedent soil water was below 60% of the available storage capacity. Details on differences in soil characteristics were also provided. Over the period of the study, the last being an incomplete year, results for approximate rainfall and runoff are summarised in Table 3.

Table 3. *Hydrological behaviour in a catchment under native forest and a catchment cleared and grazed for 80 years at Puckapunyal, Victoria (Burch et al. 1987).*

Year	***Precipitation (mm)***	***Forest runoff (mm)***	***Pasture runoff (mm)***	***Difference (mm)***
1982	266	0	0	0
1983	509	143	266	-123
1984	628	23	62	-39
1985	532	34	157	-123

A number of research catchments have been studied in Western Australia in relation to forest practices and changes in salinity. The patterns were similar to those found in southeastern Australia, however, due to differences in climate and soils, the absolute values were different. There were also different responses for different zones within Western Australia (Water Authority Western Australia 1987, Ruprecht and Stoneman 1993). For example, there were relationships between canopy cover and change in streamflow, however, in the higher rainfall Jarrah forests, a canopy of 50% had a streamflow of 40 mm while in the intermediate rainfall zone a similar canopy cover had a flow of 10 mm. These studies have not been reviewed in further detail in this regard.

4. Plantations

One of the earliest hydrology studies assessing the effect of converting dry eucalypt forest to pine planting was at established in 1967 in Lidsdale State Forest in NSW (Bell and Gatenby 1969). The study site had 11 gauged catchments representing native forests and mature radiata pine plantations. (The Stewart Creek project in Victoria commenced in 1960 and one catchment was converted to pine in 1970). The initial study (Bell and Gatenby 1969) reported on the first two years of results and concluded there was no difference between runoff from the mature pine and the native forest. Smith *et al.* (1974) compared the effect of the hydrology of mature pine and native forest over two years and his initial water balance is provided in Table 4. Since that time, there has been conversion of some of the catchments to pine, allowing for studies on younger developing plantations (for example, Knights 1983, Lambert 1979). The effect of conversion to pine in one catchment was modelled over 27 years (11 years of eucalypt forest and 16 years of pine plantation) by Putuhena and Cordery (2000). The age, and hence development of the pine plantation, had a major impact on the water balance components. The first four years after conversion was greatly different with greatly increased runoff (reduced crown and forest floor interception and reduced transpiration). As the forest developed, there was an increase in interception and transpiration with decreases in runoff and this was followed by an equilibrium situation which was assumed to continue in the mature pine stand.

Table 4. *Water balance for eucalypt and pine catchments at Lidsdale SF over a 31-month period (Smith et al. 1974).*

	Pine catchment		**Eucalypt catchment**	
	(mm)	***(% of precipitation)***	***(mm)***	***(% of precipitation)***
Precipitation (mm)	2207± 110		2268 ± 113	
Interception (mm)	414 ± 153	(18.7)	242 ± 156	(10.7)
Throughfall (mm)	1793 ± 153	(81.2)	2026 ± 156	(89.3)
Runoff (mm)	183 ± 13	(8.3)	322 ± 23	(14.2)
Soil moisture change (mm)	+23 ± 38	(1.0)	+89 ± 23	(3.9)
Evapotranspiration (mm)	1587 ± 204	(71.9)	1615 ± 202	(71.2)

The overall summary of publications on interception by radiata pine plantations and *Eucalyptus* forests (Table 5) indicates that radiata pine intercepts from 10% to 30% of incident rainfall and *Eucalyptus* spp. from 10% to 23% of incident rainfall. There is a general relationship between stand basal area and interception (Figure 2). Feller (1981a) studied the components of the water budget in two native forest stands (*E. regnans* and *E. obliqua*) and a plantation of radiata pine. The study showed that crown interception was higher for radiata pine (21%-30% of incident rainfall) than for the native forest (10%-20% of incident rainfall). No information is available on streamflow losses for radiata pine. Interception may be over-estimated in some studies since it is calculated as precipitation minus throughfall (plus stemflow) and stemflow has not always been estimated. Other studies are published but base data are not readily available (for example, Pearce and Rowe 1979, Myers and Talsma 1992)

Table 5. *Canopy interception by radiata pine plantations and eucalypt species. The stands have been ordered according to basal area in each group.*

Location / Reference	***Species***	***Age (yr)***	***Basal area (m^2/ha)***	***Rainfall (mm)***	***Interception (mm)***	***Interception (%)***
New Zealand (11)	*P. radiata*	30	102	920	237	28
Victoria (1)	*P. radiata*	15	58	1600	342	21.4
A.C.T. (6)	*P. radiata*	20	56.6	1344	400.6	23.1
Victoria (2)	*P. radiata*	38	51.2	1147	238	21
Victoria (2)	*P. radiata*	37	51	1150	347	30
A.C.T. (7)	*P. radiata*	17	49.5	734	191	26
A.C.T. (7)	*P. radiata*	17	48	603	162	27
Spain (13)	*P. radiata*	20	48.0	1360	397	29
New Zealand (10)	*P. radiata*	27	45	1510	417	28
A.C.T. (6)	*P. radiata*	30	39.1	912	232	23.5
A.C.T. (6)	*P. radiata*	16	39.1	1162	393.7	23.8
S.A. (9)	*P. radiata*	16	37.9	658	122	18.5
Chile (3)	*P. radiata*	26	36	1717	243	17.2
A.C.T. (6)	*P. radiata*	36	35.9	1188	268	24.2
NSW (8)	*P. radiata*	20	35.1	792	145	18
South Africa (12)	*P. radiata*	9	22.5	1400	171	13
NSW (4)	*P. radiata*	30	20	842	183	21.7
NSW (4)	*P. radiata*	30	19.2	871	163	18.7
Chile (3)	*P. radiata*	9	13.2	1717	322	18.7
NSW (15)	*P.radiata*	6	10	920	87	9.5
Victoria (14)	*P. radiata*	10		1130	293	26
Victoria (1)	*E. regnans*	Mature	143	1680	390	23.2
Victoria (2)	*E. obliqua*	37	65.8	1150	232	20
Victoria (2)	*E. obliqua*	38	65.8	1147	110	10
Victoria (2)	*E. regnans*	37	49.8	1631	313	19
Victoria (2)	*E. regnans*	38	49.8	1564	287	18
Victoria (1)	*E. regnans*	34	36	1680	314	18.7
NSW (4)	*E. rossii*	Mature	12	895	95	10.6
NSW (5)	*E. rossii*	Mature	12.0	870	99	11.4
NSW (5)	*E. rossii*	Mature	12.0	750	88	11.7

References

1. Langford and O'Shaughnessy (1977c)
2. Feller (1981a)
3. Huber *et al.* (1985)
4 Smith (1974)
5. Pilgrim *et al.* (1982)
6. Thistlethwaite (1970)
7. Millett (1944)
8. Crockford and Richardson (1983, 1990)
9. Ruiter (1964)
10. Will (1959)
11. Fahey (1964)
12. Pienaar (1964)
13. Calvo *et al.* (1985)
14. Visuthirungsiuri (1987)
15. Turner and Lambert (1987)

The Cropper Creek study site was established in 1975 in north-east Victoria (Myrleford) to study the effect of conversion of native forest to radiata pine plantation (Bren and Papworth 1991a, b, Bren and Hopmans 2000). There was an initial increase of 47% in water yield due to the reduction in transpiration after clearing for plantation establishment. Bren and Hopmans (2000) studied the water yield later in plantations and found that the flow measurements showed declining flow as the radiata pine aged. At 17 years, the plantation water use was slightly more than that of the native eucalypt forest. However, thinning of the plantation (30% of basal area) reduced tree water use and significantly increased water yield in the year of thinning and immediately after that.

The Red Hill Hydrology Project was established in 1989 by State Forests of New South Wales to assess the impacts of pine plantations established on pasture sites. The site is near Tumut in NSW and involved two small catchments nested within a larger catchment. One of the small catchments was retained as pasture as a control. Major *et al.* (1998) provided the establishment report together with initial analyses of runoff up to 8-9 year old radiata pine. They reported a decline in runoff with increasing plantation age indicating additional water use (over the pasture) of 200-250 mm annually. This was analysed in detail by Webb and Kathuria (2007) and looked at the decline in runoff as the plantation developed but also included the increase in runoff when the plantations were thinned and they discussed silvicultural options impacting on hydrology. However, subsequent reporting on the flows indicated that there had been a levelling out of the reduction in the loss (Vertessy 2001, Figure 3). The study was used as a basis for modelling longer term land use changes in the larger Adjungbilly Catchment (38,900 ha) (Munday *et al*. 2001). Over the period of study, the catchment changed from 60% pasture and 40% native forest in 1944, to 65% pasture, 5% plantation and 30% native forest in 1968, through to 50% pasture, 15% native forest and 35% plantation in 1998. The model adequately predicted the magnitude and nature of the change and there were increasing flows as the area of pasture increased, followed by declines in flow as plantation area increased, however, the overall trend in streamflow change was statistically insignificant.

At Stewart Creek in Victoria, a series of treatments were imposed on four research catchments in 1960. All four catchments were native forest at the commencement of the study and there was a calibration period of about eight years prior to treatments being applied. One catchment was converted firstly to pasture and then planted to pine plantation (Nandakumar and Mein 1993). The clearing of forest led, in all cases, to an increase in water flow from the catchments. The establishment of pine led to a progressive decline in this enhanced flow until, by 18 years after planting, the flows were back to that of native forests. If the flow under pasture was assumed to be the baseline, there was a period of about five years followed by a decline in flows and this decline continued to about 18 years of age. No activities, such as thinning, were undertaken within the forest. The difference between Red Hill and Stewarts Creek was no increase in flow occurred at time of clearing of Red Hill due to relatively minor existing vegetation (Figure 4).

A study site in Queensland, Sandy Creek, evaluated the effects of harvesting and thinning (Bubb *et al.* 2002) of mature pine. No significant effects of thinning or harvesting were found on water quality parameters. Harvesting increased streamflow by up to 27%, measured for two years after harvesting, but this was expected to last 4 to 10 years (related to redevelopment of the plantation). Nutrient loadings and concentrations were also reported.

A general review of coniferous plantations in NSW was undertaken by Cornish (1989) and the information has been used in later modelling studies. A critical aspect is the scaling up of data from small to large catchments especially since it is recognised that not all components or catchments are equivalent (Pilgrim 1983). In a review of effects of plantations on water flow, Vertessy and Bassard (1999) and Vertessy *et al.* (2003) concluded that "large-scale plantation development will exert additional pressure on a water resource system that is already under considerable stress. Tree planting will reduce river flows and recharge to groundwater and in certain circumstances, may lead to short-term worsening of river salinity prior to any improvement. Reductions in flow will be particularly problematic during dry spells when water resources are sorely stretched. Most of the likely hydrological impacts of afforestation can be predicted using current catchment models, but new field data are needed to test and improve their accuracy. Reduction in river flow induced by afforestation can be minimised with careful planning, and various strategies to minimise impacts are recommended". The discussion was based on the curves reported by Holmes and Sinclair (1986) and Zhang *et al.* (1999) relating mean annual evapotranspiration (and by difference, mean annual runoff) of forested and grassland covered catchments, with mean annual rainfall (Bradford *et al.* 2001). Following such analyses, it has been commented that within larger catchments, only a small proportion of the total area will actually be planted (for example, Bristow 2003).

In New Zealand, a number of studies have been undertaken. A large scale analysis of radiata pine plantation establishment was undertaken by Dons (1986, 1987) on the North Island of New Zealand. The Tarawera catchment is 90,600 ha in area and 28% of this was planted to radiata pine between 1964 and 1981. Comparing the flows from this catchment with adjacent catchments which had not undergone land use change indicated that the plantations had resulted in a 13% decrease in mean flow. There were other decreases attributed to decreased rainfall during the period. An analysis of a range of studies was undertaken by Fahey (1994) who reported on conversion of native forest, tussock and pasture to radiata pine plantation. Forests influence water yield and associated streamflow responses through increased canopy interception of rainfall. Thus afforestation of pasture sites may reduce water yield by 30-50% at 5 to 10 years after planting. For tussock grass, the reduction may be 25-30%. Silvicultural practices such as understorey control and spreading of the time of planting, have the potential to augment yield. It was noted that forest harvesting in moderate to high rainfall areas can cause a 60-80% increase in water yield for three to five years after clearfelling. The total effect is a requirement for a balance of age classes, silvicultural activities and harvesting to maintain hydrologic values in a catchment.

Smith (1987) studied the differences between two grassed and two plantation catchments where the plantations were 14-years-old when the study commenced. Over the study period, there was an average decline in runoff of 17.2% in the pine plantations. A study on the hydrological effects of converting lightly grazed mid-altitude tussock grassland to *P. radiata* plantation examined paired catchments in east Otago (Fahey and Watson 1991). After three years of calibration, 67% of one catchment (310 ha in area) was planted to radiata pine in 1982. There was no change in water yield for six years after which runoff declined by 100 mm or approximately 10.3%. Peak streamflows were most affected by the plantings but analysis indicated that low flows were also affected. It was considered that the reductions in runoff were mainly a result of higher canopy interception.

Fahey and Jackson (1997) reported on two long term studies in New Zealand, namely the conversion of native forest to pine plantation and conversion of native grassland to pine plantation. The conversion of the native forest (mixed evergreen forest) to pine plantation was studied in a control catchment and two catchments with different methods of harvesting. The first four years after harvesting led to a water yield increase of between 61% and 68% with a return to the water yield at pre-harvest in both treated catchments at 8 years after harvesting after which there was a reduction in runoff. Tree growth brought storm peaks, quickflows, and low flows back to the levels of those of the original beech forest within 10 years. The study was on conversion of tussock grassland to pine. There was a gradual reduction in water yield in the planted catchment and by about age 10 years, this equalled a reduction of about 27%. Differences in low flows showed a similar trend. Higher interception losses were considered to be the main reason for the change. After 10 to 12 years of tree growth, mean flood peaks had fallen to between 55% to 65% and quickflows by 50%.

Fahey *et al.* (2001) also compared the water loss from different species (Douglas-fir and radiata pine) at a site in New Zealand. The pattern indicated that Douglas fir had higher interception and transpiration than radiata pine and consequently lower runoff. This indicated that the components of the water balance vary according to species and stage of development. Dons (1986) studied the effect of plantations on hydrology in permeable pumice soils in the North Island of New Zealand. The pine forest reduced flows compared with native vegetation and the flows were much greater when compared with pasture catchments but sediment yields were also low.

Hydrology studies have been undertaken extensively in Africa, especially where natural grasslands are being converted to exotic plantation, both coniferous and eucalyptus species. Under these conditions, significant reductions in soil water and runoff water have been found as a result of plantation establishment (Bosch and Smith 1989). South African forest plantations by virtue of their presence in very limited areas with high rainfall, and their increased water use relative to pre-afforestation vegetation, have resulted in significant reductions in streamflow from afforested catchments. Water supply is an issue and will become more important in the future.

Van Wyk (1987) reported on long term studies of plantation establishment in the Western Cape Province of South Africa. Streamflow was monitored from 1940-1980 and afforestation resulted in reduced streamflow. In the case where 98% of the catchment was afforested, annual streamflow decreased by 313 mm from an initial 663 mm to an average of 350 mm/year over a period of between 12 and 32 years after afforestation and streamflow then stabilised at this level. In the catchment with 57% afforestation, streamflow declined by 200 mm/year from an initial 593 mm/year over a period of 16 to 40 years after afforestation. Here, streamflow stabilised at about 20 years. Percentage of area afforested, total biomass and rainfall appear to have influenced the magnitude of reductions in streamflow. A comparison of catchments, originally grassland, converted to *E. grandis* or *P. patula* plantation was studied. The effect of harvesting the eucalypts at 16 years of age was also assessed. Afforestation of an entire catchment with eucalypts with a virgin annual runoff of 236 mm, caused a statistically significant decrease in streamflow in the third year after planting and the stream dried up completely in the ninth year after planting. The eucalypts were clearfelled when 16-years-old but full perennial streamflow did not return until five years later. Afforestation of an entire catchment with pines with a virgin annual runoff of 217 mm, produced a significant decrease in streamflow in the fourth year after planting and caused the stream to dry up completely in the twelfth year after planting. The drying up of the streams was not altogether surprising as the annual runoff was lower than the expected reduction owing to complete afforestation. The delayed return of streamflow in the clearfelled catchment is surprising though, and was attributed to the desiccation of deep, soil-water stores by the eucalypts. These stores had to be replenished before the streams could return to normal behaviour.

Dye (1996) reviewed relationships indicating increased evapotranspiration, reductions in water in soil profiles and other hydrological changes as a result of plantation establishment on what was grass or shrubland (Fynbos). Bosch and Gadow (1990) addressed the questions of water conservation and forestry under South African conditions. They developed linear models to analyse effects of plantations and to use as a planning tool. The locations of plantations in a catchment, especially in relation to drainage lines, were reported to be a critical issue in regard to impacts on runoff. Of interest is an analysis of species differences where in short rotations, pines used less water than eucalypts but had equivalent uses in longer term plantations. Part of this was due to interception differences.

Mwendera (1994) studied a catchment in Malawi in a 1300 mm rainfall area which had been converted over a period to a pine and a eucalypt plantation. No significant differences were found in the rainfall patterns and peak stream flows before and after afforestation, however, the minimum flows were reduced as a result of planting. It was concluded that the high water use was due to additional transpiration during the dry period.

The water balance in radiata pine was studied by Calvo *et al.* (1985) in relation to studies on potential effects of plantations on soils. Compared with native oak stands, runoff (measured on a plot basis) was reduced due to higher productivity and water use by plantations.

There is a often a problem with the use of small catchments in that a large proportion of the catchment (often 95%) is planted and hence hydrologic impacts are maximised. In practice, however, plantation development is regulated (for example, State Forests of NSW 1997), identifying where plantations can or cannot be established. Limitations include the presence of native vegetation, topography, and drainage requiring buffer strips. Additionally, within the planting area a significant proportion is retained on roads. The effect in any one year is that about 70% of a property may be planted. In a larger catchment, there will be a distribution of activities which need to be integrated to see the total effect on runoff. They can include:

- A proportion of native forest retained;
- A proportion of pasture land;
- Cleared areas prepared for plantation;
- Young developing plantation;
- Plantation at full canopy development;
- Plantation thinned with reduced canopy; and/or
- Areas harvested.

5. *Water Quality*

Changes in land use and management practices affect water quality. Water quality assessments have been undertaken in research projects and in a number of studies, and there has been some monitoring at the research level. The objectives, logistics, scale, costs and interpretation are issues that need to be addressed in any monitoring program.

Cornish (1980a) reviewed water quality from “grab samples” in native forests which had been harvested on the north coast of NSW. It was concluded that the effect of logging operations was slight on the measured parameters. A similar study was undertaken on the south coast (Cornish 1980b) and there were comparable results.

Grayson *et al.* (1993a) developed a “snapshot” system for assessing point and non-point source loadings in the Latrobe River catchment. For logistical reasons, water quality is normally monitored on a regular basis at only a small number of locations in a catchment, generally at the catchment outlet, and as such processes within the catchment are integrated. The”snapshot” sampled a larger number of sites at low flow; in this case 64 sites were sampled. Such an approach was considered to provide a cost effective approach for understanding variability within the catchment. The alternatives based on objectives were initially outlined (Figure 1).

The “snapshot” approach to sampling was undertaken at Bago State Forest to test strategies (Turner *et al.* 1996a). The sampling involved taking samples from a large number of sites in an area within a short space of time to evaluate spatial variation and identify sites with high (relatively) pollutant input. By locating sites to be representative of geology and land use, causes of variation could be attributed. Reporting was on a concentration basis and also by allocating quality per length of creek (rather than as point location reporting). Sampling was undertaken in native hardwood (34 sites), pine plantation (16 sites) and cleared land (38 sites). The study (within significant basalt areas) differentiated land use and geology for most parameters measured. The median turbidity of hardwood, plantation and cleared land was 2.1, 3.2 and 4.9 NTU respectively. The study was repeated in the Towamba Valley Catchment (Turner *et al.* 1996b) and the Bega Valley Catchments (Turner *et al.* 1998). There is a broader range of land uses in the latter catchment than in the Bago study.

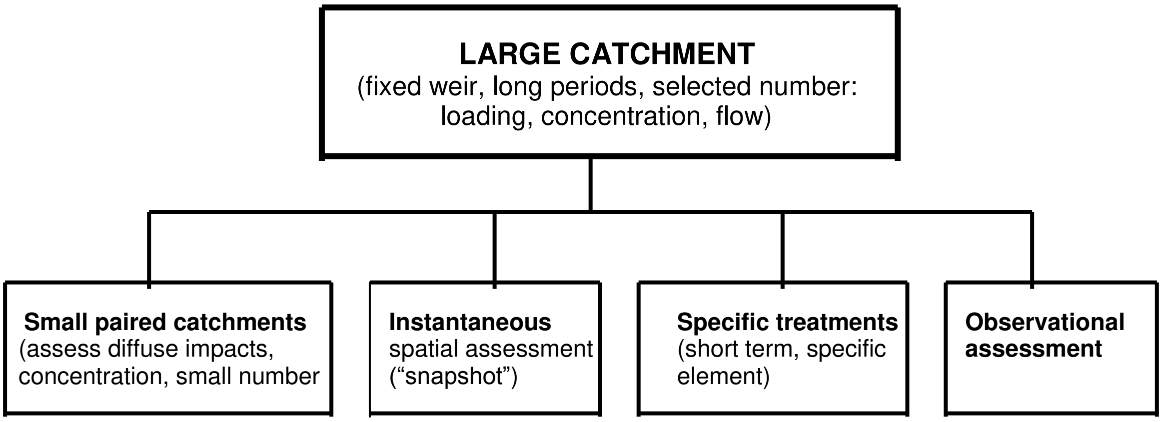

Figure 1. *Hierarchical system of water quality sampling at the Management Unit level within forests (Turner et al. 1996a).*

The information on nutrient exports in relation to land use in Australia was reviewed by Young *et al*. (1996). The focus was on causes of eutrophication and hence on nitrogen and phosphorus. They concluded that Australian data on nutrient losses and land use were sparse, and that the supplementation of data from North American conditions was not suitable. Data from southeast Australia are presented in Table 6. The forest data include native forests and plantations.

Table 6. *Average annual nutrient export (kg/ha/yr) in southeast Australia from Young et al. (1996).*

Type of Broad Land Use	***Total Phosphorus***		***Total Nitrogen***	
	Range	***Typical***	***Range***	***Typical***
Market gardens	2.7- 14.3	7.1	20- 34.5	26
Urban	0.4- 3.6	1.0	3.2- 22.4	6.6
Improved pasture	0.1- 0.7	0.3	0.6- 4.6	3.3
Unimproved pasture	0.07	0.07	2.2	2.2
Forests	0.03- 0.1	0.06	0.9- 1.5	1.1

The above data support overseas studies indicating there are differences in nutrient exports depending on geology and land use. For example, Dillon and Kirchner (1975) studied phosphorus loadings in Ontario, Canada (Table 7).

Table 7. *Range and mean values for export of total phosphorus (kg/ha/yr) from 31 southern Ontario watersheds (Dillon and Kirchner 1975).*

		Geological Classification	
Land Use		***Igneous***	***Sedimentary***
Forest	Range	0.025-0.077	0.067-0.145
	Mean	0.048	0.107
Forest and Pasture	Range	0.081-0.160	0.205-0.37
	Mean	0.117	0.288

In New Zealand, a study on land use reported differences in losses of nitrogen and phosphorus (McColl *et al.* 1977). The total losses were reported and also partitioned according to rainfall events indicating that a major proportion of losses occurred in high rainfall events (Table 8). The results for Red Hill catchment in NSW were lower for N and P export than reported in table 8 (Vink et al 2007).

Table 8. *Loses of nitrogen and phosphorus from catchments with different land uses in New Zealand (McColl et al. 1977).*

	Total phosphorus (kg/ha/yr)	***Nitrate nitrogen (kg/ha/yr)***
Native forest catchment	0.2009	0.0115
Pasture catchment	0.2929	0.1356
Radiata pine catchment	0.0706	0.0444

The actual balance of inputs and outputs has also been addressed at the small catchment level. Flinn *et al.* (1979) reported the annual inputs and losses of nutrients for the year 1977. Nutrient losses (kg/ha/year) in streamflow were found to be very low as runoff represented only 7% to 14% of the total rainfall. The nutrient balance, averaged over the three catchments prior to treatment, is provided in Table 9.

Table 9. *Inputs and losses of nutrients from selected forest catchments in Australia.*

Project	***Nitrogen***	***Phosphorus***	***Potassium***	***Calcium***	***Magnesium***
			(kg/ha/yr)		
➢ ***Cropper Creek (Flinn et al. 1979, Bren et al. 1979, Hopmans et al. 1987)***					
Rainfall Input	0.319	0.009	1.818	3.253	1.103
Runoff losses	0.012	0.004	0.426	0.588	1.295
Balance	**0.307**	**0.005**	**+1.392**	**+2.665**	**-0.192**
➢ ***Daylesford (Guthrie et al. 1978)***					
Rainfall Input		0.52	0.115	0.645	
Runoff losses		0.81	0.05	1.200	
Balance		**-0.29**	**+0.065**	**-0.555**	
➢ ***Maroondah (Feller 1981b)***					
Myrtle 1					
Balance	**-1.8**	**+0.01**	**-3.2**	**-5.0**	**-2.4**
Myrtle 2					
Balance	**-3.4**	**-0.05**	**-5.9**	**-9.4**	**-5.3**
➢ ***Yambulla (Losses in Mackay and Robinson 1987, Inputs in Turner et al. 1996c)***					
Pomaderris (control catchment 8 years)					
Rainfall inputs	0.25	0.045	1.74	2.1	1.84
Runoff losses	0.063#	0.024#	1.97	1.54	1.92
Balance	**+0.24**	**+0.021**	**-0.23**	**+0.56**	**-0.08**

 # Approximate estimates

In forestry operations (native and plantation), it is recognised that the main source of sediment, and consequent effect on water quality is from roads (Iroume 1990, Croke 1999, Croke *et al.* 1999, Hopmans and Bren 1999). Hence location and maintenance of roads is a critical issue in reducing sediment loads.

Plantations have been proposed to ameliorate the impacts of increasing salinity, especially in the areas below 700 mm annual rainfall. This has been reviewed in detail (Lambert and Turner 2000) but the critical factors include:

- The ability to lower rising watertables and their contained salts.
- The importance of identifying critical areas in the landscape to maximise impacts.
- Required scale of planting.
- Recognition that all areas are not equal in effect.
- Ability to monitor and interpret the interacting effects.

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Appendix 1. *Tabulation of studies on catchment hydrology in Australia.*

Location or Project	*Vegetation*	*Parent Material*	*Mean Rainfall (mm)*	*References*	*Subject*
Cropper Creek (Myrtleford, Vic)	Native forest	Shale	1200	Flinn *et al.* (1979) Bren *et al.* (1979) Bren and Papworth (1991a,b) Hopmans *et al.* (1987) Hopmans and Bren (1999)	Nutrient balance Establishment study Establishment study Nutrient balance Nutrient balance
Yambulla Project (Eden, NSW)	Native forest	Granite		Mackay *et al*. (1980) Mackay and Cornish (1982) Mackay and Robinson (1987) Burgess *et al*. (1980) Cornish and Binns (1987)	Fire effects Fire effects Water quality Fire and harvesting Fire and harvesting
Tantawanglo (Eden, NSW)	Native forest	Granodiorite		Wronski (1993) Bek (1985) Lane and Mackay (1997)	Harvesting Baseline study Harvesting
Karuah (Newcastle, NSW)	Moist native forest	Sediments		Cornish (1993)	Harvesting
Red Hill Station (Tumut, NSW)	Pasture/ Pine Plantation	Granodiorite/ Diorite		Major *et al*. (1998) Webb and Kathuria (2012) Vink et al. (2007)	Plantation effects Water yield Nutrient balance
Sandy Creek (Toolara, Qld)	Mature pine	Sediments		Bubb *et al.* (2002) Bubb (2001)	Harvesting Thinning
Melbourne Board of Works (Victoria)	Native forest	Granites	1600	Dunn and Conner (1993) Hatton and Vertessy (1990) Haydon *et al*. (1996) Jayasuirya *et al.* (1993) Vertessy *et al.* (1993) Vertessy *et al.* (1996) Vertessy *et al*. (1998) Kuczera *et al*. (1987) Langford (1976) Langford & O'Shaughnessy (1977a, b, c)	Transpiration Transpiration Transpiration Fire & water yield Water yield Water yield Water yield Fire & water yield Fire Fire & water yield

Appendix 1. *Cont.*

Location or Project	***Vegetation***	***Parent material***	***Mean Rainfall (mm)***	***References***	***Subject***
Lidsdale (NSW)	Native woodland	Sediment	800	Bell and Gatenby (1969)	Pine planting
				Smith (1974)	Pine planting
				Smith *et al.* (1974)	Pine planting
				Knights (1987)	Pine planting
				Lambert (1979)	Nutrient cycling
				Pilgrim *et al.* (1982)	Water yield
				Putuhena & Cordery (2000)	Water yield
Stewart Creek (Vic)	Native forest	Sediment	800	Nandakumar and Mein (1993)	Pine planting
				Guthrie *et al.* (1978)	Nutrient cycling
Yass Valley (NSW)	Native woodland	Sediment	750	Crockford & Richardson (1983, 1990)	Pine planting