Report:
Trees for steep slopes

supported by forest growers commodity levy

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Executive summary

The Joint NZ Farm Forestry Association/Forest Owners Association (NZFFA/FOA) Environment committee commissioned this report to consider and explore species and management options that might minimise soil erosion in highly erodible hill country while maintaining productivity of the land.

This report assembles information for growers and territorial authorities to be well informed on plantation forestry options for steep slopes and hill country that mitigate the risk of erosion. The focus is on alternative species **and** regimes that offer the opportunity to improve slope stability beyond what can be achieved with standard practice radiata clearfell practices. However, it should be noted that New Zealand-based research quantifying the effectiveness of alternative exotic forest species in mitigating erosion is scarce, as is evidence of the suitability and growth performance of these species when grown on steep (and generally less fertile) slopes, or that they will be profitable. Filling these information gaps would better inform land managers of the range of species best suited to different terrain types and most likely to fulfil environmental obligations under the National Environmental Standards for Plantation Forestry (NES-PF).

National Environmental Standards for Plantation Forestry (NES-PF)

The NES-PF specifies that erosion-prone (ESC red zone) land can now only be planted or replanted with a territorial authority resource consent and the application will be subject to a detailed risk assessment. Although the aim of the risk assessment is to mitigate significant adverse environmental effects, such as storm-initiated slope failures with the potential to form debris flows that could result in significant damage to downstream infrastructure and property, this requirement may potentially increase compliance costs, particularly for growers operating in steeper terrain.

Marginal or negative returns for forestry on steep slopes may lead to plantation forest activities being shifted away from the steeper landforms most in need of forest cover, onto more stable landforms. If this were to occur the overall environmental outcome would not improve because the steepest, most erosion-prone land would likely remain in pastoral use and at increasing risk to further erosion.

Standard-practice radiata pine clearfell regimes are no longer a permitted activity on steeper (red zoned) slopes greater than 2 hectares. In order to retain an erosion-mitigating forest cover, alternative regimes and/or species will be required, along with evidence that significant adverse environmental effects can be minimised. Of course, the other option is to retire land from productive use to become private conservation forest, but this will result in reduced wealth generated from the primary sector. An improved understanding of risk and erosion thresholds would therefore better inform decisions on future land use options, particularly for steep hill country, keeping in mind that ecosystem services function best when there is a revenue base from the activity to maintain them, which might not occur in the private conservation estate.

Erosion mitigation practices

A national erosion susceptibility classification (ESC) has been developed to support the NES-PF. Current limitations of the ESC include the scale of mapping, the quality of underlying data and misclassification of land (Phillips et al. 2017).

For red-zoned land, in the absence of evidence supporting risk mitigation measures, the adequacy of such measures would be at the discretion of territorial authorities. Although the risk level itself can be assumed from the ESC; setting conditions for consent to meet specific performance thresholds such as estimated sediment yields would need to somehow match the ***measure*** to the ***risk.*** This could potentially be achieved by factoring in:

- Tree stocking rates so as to shorten the duration of the 'window of vulnerability' (i.e. time for the roots of the new planting to replace the rotting roots from the previous rotation). Slower-growing species and sites with low site index would require a higher stocking;
- Rotation length for alternative commercially viable species;
- Measures that restrict the likelihood of landslide occurrence that could form debris flows.

Additional research is needed to quantify the erosion-control effectiveness of "alternative" species to radiata pine (exotic and indigenous). Furthermore, there is a need to better understand relationships between alternative species restocking rates on forest cutover, and their level of effectiveness in mitigating post-harvest sediment generation rates, relative to that measured for radiata pine planted at the same densities. Although detailed information on how different species reinforce soils (such as lateral root reinforcement versus vertical anchoring) would be useful within a comprehensive research strategy, the immediate priority could instead focus on simple models of species-specific, post-harvest rates of root decay and for juvenile plants to establish the growth rates and above-ground tree performance (tree height, canopy width, tree biomass) to be able to predict and define the time it takes for canopy closure to occur according to stocking rate. Managing effects and consequences of erosion could then be simplified to the relationship between the mitigation measures themselves, and for example reduced levels of sediment or reduced occurrence of debris flows that exit the forest boundary.

Estimating the effect that mitigation activities would likely have on consequences of erosion would offer immediate security in terms of the plantation forest industries social licence to operate in erodible steeplands. Additionally, it will provide more scientifically robust evidence in support of the effectiveness of alternative species or regimes in mitigating surface erosion processes, and in reducing the occurrence of shallow landslides during storm events, that will greatly assist territorial authorities during the consenting process. Fine-tuning trade-offs between economic and environmental outcomes may be possible as more empirical evidence becomes available over time. Benchmarking levels of pre- and post-harvest erosion against the status-quo pastoral land use when seeking territorial authority permission to afforest steeplands may also provide useful decision-making tools for both landowner and regulator.

Research is also required that quantifies productivity gains from innovative practices by foresters who have recognised problems and produced solutions to these. Although satisfied with their solutions in terms of their own operation, other operators may not be aware of such innovative practices or paradigms. Although a "no worker on the slope, no hand on the chainsaw" policy is a worthy vision of Forest Growers Research for larger-scale harvesting operations, at the smaller scale sustainable harvesting of steeplands might best be optimised by innovations that involve less mechanisation and improve efficiency only at that scale. Resources are required to support and encourage innovation at the smaller scale and in particular continuous cover harvesting or small coupe harvesting efficiency.

Economics

For growers to deploy a species and regime at any scale, models would also be required that estimate returns according to rotation length or harvest regime, taking into account initial stocking and thinning practices that mitigate erosion. Extending the rotation length is desirable for reducing erosion over time, but it has negative impacts on economic rates of return. Slower growing species that yield high-value timber may offer an appropriate trade-off that satisfies both growers and territorial authorities. Alternatively, faster growing species managed as a continuous cover forest may prove to be profitable and environmentally sustainable on steeper slopes.

Estimating profitability should take place at the same time as quantifying the level of erosion mitigation for that regime.

Tree species and regimes

Rate of root decay is species dependent, as is growth rate. Increasing replant density for radiata pine on steeper slopes narrows the window of vulnerability time period, therefore models are required that define planting density according to risk, along with restocking rate on a species by species basis (Phillips et al. 2012).

Some timber species are far better suited to continuous cover management than radiata pine, primarily because they are more shade tolerant. Continuous cover forestry is clearly the "gold standard" for mitigating erosion resulting from harvesting. However, measures available to reduce erosion in a clearfell regime include:

- undertaking only best-practice earthworks (e.g. as per NZ forest road engineering manual);
- minimising soil disturbance and compaction when harvesting;
- managing slash to minimise risk for entrainment in debris flows;
- providing buffers between productive areas and water courses that act as slash traps;
- Identifying areas with excessive risk of erosion and retiring these from productive use.

Replanting or planting at high initial stocking rates and reinstating vegetative cover as soon as possible after harvesting are also important practices that mitigate erosion after clearfell harvesting.

Some timber species appear well-suited to preventing erosion because they coppice from the stump, so their soil-reinforcing roots stay alive. The roots of other species decay at a slow rate and continue to reinforce the soil for longer than low durability species such as radiata, allowing the next crop to establish before those roots lose their soil-reinforcing properties. This window of vulnerability for each species is therefore based on species root decay rate along with the time it takes for the next crop to attain canopy closure. The duration (number of years after planting) of this window of vulnerability is influenced by both the stocking rate (planting density) and species growth rate, thus a stand established at a high tree stocking using a fast growing species will attain canopy closure sooner than a stand established at a low stocking or with a slow-growing species.

Some specialty timber species could potentially be profitably grown on long rotations because of their high timber value. High-value species can also be managed as a continuous cover with supply matched to demand.

Unfortunately, detailed estimates of returns or timber values according to species or regime are not currently available. Indeed crystal ball-gazing may give better predictions of future timber values according to specific applications the timber may be used for, than thoroughly-researched predictions based on current timber values and speculative assumptions, because timber markets and values change in unpredictable ways.

Erosion risk will always remain to some degree unpredictable. Clearfell harvesting does have environmental consequences on steeplands. Managing erosion levels resulting from harvesting involves trade-offs between the grower's bottom line and environmental sustainability, with single-tree extraction methods being the most environmentally benign but also the highest cost.

All tree species require correct siting. Selection of species would principally consider suitability for the site. However, in general terms, by provisionally (in the absence of comprehensive data) rating early growth rate, suitability for continuous cover, root decay rate, productivity, timber value and ability to coppice, the four most suitable "alternative" species for steeplands are:

- Eucalyptus (stringybark/ash)
- Redwood
- Cypress
- Poplar

However, it should be noted that poplar and redwood are limited to sites that have reasonable shelter and fertility, generally lower slopes.

Totara shows the most promise among the native species in terms of overall potential as a profitable and productive plantation species. There are a number of other species available, including native species, that produce high-value timber on longer rotations than radiata pine, so offer options that could potentially reduce the erosion risk while still providing an acceptable level of return.

Introduction

The National Water and Soil Conservation authority issued the warning fifty years ago that New Zealand was still losing its agricultural soil and production levels were continuing to decline in erodible lands (NWSCA 1985). This despite regulatory actions implemented in 1941 designed to stem the loss of soil from our pastoral slopes. Soil erosion continues to be one of New Zealand's most serious environmental problems (Hocking, 2006a), with over 60% of land steeper than 15 degrees being inherently unstable (Eyles, 2014). In contrast, soil erosion under standing forest is very low (Elliot et al. 1999), provided there is full root site occupancy and canopy closure (Basher et al. 2008).

The issue appears to be that "New Zealand is unique in the way it uses its steep and often unstable hill country for pastoral farming, grazing predominantly sheep and beef cattle but also deer. Stock remain on the hills all year round" (McIvor et al. 2011).

The result is that in steeper hill country underlain by poorly consolidated parent materials, pastoral agriculture "will come increasingly under threat from the progressive reduction of pasture production through cumulative erosion." (McIvor et al. 2011).

This outcome is neither desirable for land owners nor New Zealand society.

Soil Erosion in New Zealand

Soil is formed by the gradual breakdown of rock material from chemical and physical weathering processes along with decomposition of vegetation and fauna. There is an equilibrium between soil formation and erosion under normal geological erosion processes whereby rocks weather and produce soil, along with "a gradual process of removal of weathered rock from the hills to the lowlands" (Grange and Gibbs, 1948). However "accelerated erosion" results from altering the vegetation cover (Grange and Gibbs, 1948).

The effects of erosion are either on-site (e.g. loss of productivity) or offsite (e.g. loss of water quality, river aggradation, damage to infrastructure) (McIvor et al. 2011). Loss of soil productive capacity results from the loss of mineral nutrients, lower soil moisture holding capacity and a reduction in soil organic matter (Elliot et al. 1999).

The origins of soil erosion in New Zealand

Prior to the arrival of humans much of New Zealand was cloaked in indigenous forest. Clearance using fire and the introduction of browsing animals weakened the soil matrix and dramatically accelerated erosion, with catastrophic results such as severe flooding and debris carried down to the lowlands (NWSCA 1985).

Forest cover was reduced from approximately 50% of New Zealand's land area in 1840 to 18% by 1920 (Jones et al. 2008). Historical clearing of bush for farming had significant negative effects on water quality and hill country soils in many parts of New Zealand. Howard (1976) described the consequences of clearing bush for pastoral farming in the East Cape between 1890 and 1910: “The roots of the trees that had been burned or cut had rotted, and the ground gave way... We lost a lot of our grazing area... and a few animals”. The erosion itself was described by Howard (1976) as ”Huge earthflows – slow, creeping slips – appeared on the gentler slopes. In other faces, slumping happened. A great crack would appear on the surface, and the ground would sink. Also, floods became a bigger problem as the riverbeds filled up... Some people wrote about the dangers of erosion back in 1920, but nothing was done. The years passed, the farmers went on farming, and things got worse each year”.

Most of New Zealand's erosion-prone land remains in pasture and pastoral farmers have been slow to adopt land use practices that are sustainable (Knowles, 2006). Approximately 200,000 hectares of North Island hill country has a severe, very severe or extreme potential to erode and "New Zealand makes up ~0.1% of the global land mass yet discharges 1-2% of the average annual sediment yield to the world's oceans" (Jones et al. 2008; Hicks and Shankar, 2003). Increased sediment loads in rivers resulting from hillslope erosion results in damage to infrastructure, including tracks, roads, culverts and fences, with sediment deposited on flood plains and near shore sea beds (Hocking, 2006a).

Loss of pasture production results from erosion scars, which can be reduced to 20% of pre-erosion levels, recovering only slowly to eventually be 70-80% of the un-eroded level (Lambert et al. 1984, Rosser and Ross, 2010 in McIvor et al. 2011). Not only is productivity reduced because of loss of organic matter, nutrients and soil depth, soil structure is adversely affected, reducing infiltration rates and water holding capacity (Jones et al. 2008).

Intensification of farming with the emphasis on animal productivity, and in particular the grazing of steeper slopes, not only risks negative market exposure for New Zealand's animal products, but by not recognising the physical limitations of different land classes the negative environmental consequences of erosion remain ignored (Eyles, 2014).

Hill country land never fully recovers from past slip erosion and pastoral production levels continue to decline in erodible lands (NWSCA, 1985). The national economic cost of soil erosion and sedimentation was conservatively estimated to be $126.7 million per year in 2001 (Krause et al. 2001). However, because the economic consequences of cumulative erosion in pastoral hill country are not well researched in New Zealand (McIvor et al. 2011), there remains no immediacy behind any collective mandate for change. Furthermore, land use practices reflect underlying environmental values held by land owners, therefore by not addressing behavioural and social drivers of accelerated soil erosion, market and voluntary actions alone do not result in a more efficient pattern of land use (Basher et al. 2008).

Land use and erosion

The connection between removing forest cover, erosion and flooding has been well accepted for some time, but only since 1941 when the Soil Conservation and Rivers Control Act was passed, has soil conservation been regulated in New Zealand (NWSCA, 1985).

Slip erosion occurs in hilly and steep land and is considerably accelerated by removing forest vegetation and replacing this with a pastoral land use (Grange and Gibbs, 1948). Conversely, the likelihood of slip erosion occurring is reduced by a cover of dense vegetation, which protects and binds the soil (NWSCA, 1985). The rock type exposed by slips determines the subsequent level of vegetation growth. Where the underlying rock is soft and weathers readily, vegetation establishes more rapidly, whereas where slips expose hard rock, vegetation establishes more slowly (Grange and Gibbs, 1948).

Rainfall and slope are the two key variables that influence the degree to which soil erosion develops (NWSCA, 1985). Severe storms with high levels of rainfall increase the severity of erosion (McIvor et al. 2011), manifested in hill country as mass movement erosion and sheet erosion (Grange and Gibbs, 1948). These are the two dominant forms of erosion associated with hill country in both the North and South Islands (McIvor et al. 2011) where sheet erosion caused by surface runoff and slip erosion caused by water infiltration can be significantly reduced under a forest cover (Elliot et al. 1999).

A well established body of literature supports the benefits of a woody vegetation cover in reducing localised surface erosion and mass-movement processes (e.g. Greenway, 1987; Coppin and Richards, 1990; Phillips et al. 1990; Marden and Rowan, 1993; Montgomery et al. 2000; Phillips and Marden, 2005; Sidle and Ochiai, 2006; Phillips et al. 2012), while the afforestation of whole catchments can reduce the sediment load delivered to waterways by as much as 90% (Hill and Blair, 2005).

Slope is a key determinant of soil stability and susceptibility to erosion (Phillips et al. 1989).

Areas of steepland hill country identified as being at greatest risk to these erosion processes are those where slopes are greater than 28 degrees (DSIR 1980). Although it is recognised that erosion-prone steepland hill country that remains in pastoral use would be better in forest cover to mitigate current and future erosion issues, it is nonetheless well-documented that in production exotic forests it is during the harvest and immediate post-harvest period that cutover is most vulnerable to the initiation of surface and mass movement erosion.

Classification of erosion potential and land use capability

Mapping and classification of erosion types commenced in New Zealand during 1947 (Grange and Gibbs, 1948). Land was mapped on its erodibility or "erosion potential", taking into account vegetation cover in order to select suitable uses for land. This work led to the compilation of the New Zealand Land Resource Inventory (NZLRI) in 1973 (NWSCA, 1985). The NZLRI is a spatial land database in which land is subdivided into units or parcels based on five key physical factors– vegetation, rock type, soil, slope, and erosion presence/severity. Based on these factors, the New Zealand Land Use Capability (LUC) classification was developed to better define the quality of land including its susceptibility to erosion based on the current severity and extent of erosion, potential erosion, and hence the capability of different land use classes to sustain productivity long term. This provided a set of national standards as a basis for land use planning, and mapping. The classification consists of eight major classes of land. Class 1 land has very few limitations and has the capability to sustain a wide range of potential land uses, whereas Class 8 land has little or no inherent productive potential and is normally used for catchment protection and recreational purposes. Classes 1 to 4 are arable while Classes 5 to 8 are non-arable. Thus Class 1 land has greater land use versatility than Class 8 land which because of its physical limitations has fewer land use options that are sustainable, and there are a greater array of hazards associated with this land class (Douglas, 2011). Furthermore, Douglas (2011) suggested that "the importance of matching land use with land use capability cannot be overemphasised". The Land Use Capability handbook was first published by the Soil Conservation and Rivers Control Council in 1971 (NWSCA, 1985) and is currently available from Landcare Research as the third edition (2009).

The NZLRI also includes Land Use Capability (LUC) assessments using pastoral and forestry production parameters and data for key soil attributes, that when combined "are highly flexible in allowing comparative land use studies within a wide range of national or regional areas." (New Zealand Land Resource Inventory – Soil, 2017). However, although useful at national, regional, district or catchment levels, at a scale of 1:50 000 the NZLRI is considered to be too coarse for farm-planning activities (New Zealand Land Resource Inventory – Soil, 2017).

By combining climatic data with erosion severity potential as identified in the New Zealand Land Resource Inventory (NZLRI) and the Land Use Capability (LUC) databases, a tool called the **Erosion Susceptibility Classification** (ESC) that maps 'risk classes' was produced by the Ministry for Primary Industries (MPI) for the National Environmental Standard for Plantation Forestry (NES-PF).

Types of Erosion

Two types of erosion are important in New Zealand hill country, fluvial erosion and mass movement erosion.

Fluvial erosion is surface erosion caused by water scouring. **Sheet erosion** is the removal of the thin surface layer of soil by surface water. Sheet erosion can become **Rill erosion** when the action of water scours small channels in the soil. Rill channels are no larger than 60 cm deep and 30 cm wide (as defined by NZLRI, 1973) and develop where soil is disturbed and the vegetation cover removed. Rill channels can develop into gullies. **Gully erosion** is also caused by the channelisation of water causing scouring during periods of heavy rain. **Tunnel gully erosion** is caused by water flowing through a tunnel beneath the soil surface. Eventually the roof of the tunnel collapses to expose the underlying gully.

Large-scale gullies develop when the protective vegetative cover is lost and once initiated their development is difficult to stem. Gully erosion is a very destructive form of erosion and is the largest sediment-producing process in many New Zealand river systems, particularly in the East Coast region of the North Island (Marden, 2009). The most effective method for controlling actively eroding gullies and reducing sediment production from them is reforestation (Marden, 2009). Although reforestation is also the best means of preventing the initiation of new gullies, once gullies form they are most easily stabilised while new and small, because if allowed to develop into larger gullies reforestation can take considerably longer to stabilise them (Marden, 2009).

Mass movement erosion is gravitational driven movement of soil mass downhill. **Landslide** and **soil slip erosion** is where subsidence is rapid. Nearly a third of the land area in the North Island is affected by slip erosion, making it the "most extensive and economically important erosion process in the North Island" (NWSCA, 1985). Consequences include silted drains and watercourses and reduced production potential. The occurrence and severity of landslide erosion is described by NWSCA (1985) as "depending mainly on the steepness of slope, the underlying rock type and the vegetation cover. Soil slips are most likely to occur on steep slopes and are rarely found where slopes are less than 16° ". Where landslides are deeper, failure can occur within the subsoil deposits or at the contact between the subsoils and the underlying bedrock. Typically the depth of failure is less than 1 m below the original soil surface (Marden et al. 1991; Page et al. 1994).
Where the landslide involves movement of a mass of soil and underlying material while leaving the surface vegetation relatively intact, this is known as an **earthflow**. **Debris avalanches** occur on steep slopes and incorporate large volumes of material. Failure of the slope occurs rapidly and as the failed material moves downslope it creates a scar referred to as a debris trail. Where a large mass of hillside fails and also rotates backwards as it slides on a concave slope, this is known as a **rotational slump**.

Risk of erosion

The risk of the occurrence of erosion is determined by factors that predispose land to erosion, along with the likelihood of events that trigger erosion (Saunders and Glassey, 2007). Estimating erosion susceptibility involves the interaction between these two factors (Bloomberg et al. 2011). Increased slope and higher rainfall are the most important factors that influence "risk". The result is that unstable geological terrain located within high rainfall zones generate high sediment yields (Blaschke et al. 2008), a negative environmental consequence that can be related back to land use.

Topographic and physical characteristics such as slope, drainage, type of bedrock and soil type influence the likelihood for land to erode (Bloomberg et al. 2011). However, perhaps more importantly, management practices also either mitigate erosion risk, or increase it (Bloomberg et al. 2011). Removal of vegetation cover increases the risk of erosion and afforestation reduces the risk (Bergin et al. 1993). Earthworks can mitigate erosion by stabilising slopes, or prepare land for erosion by inadvertently changing drainage patterns.

The Case for Land Use Change

Soil loss increases ten fold after conversion of forest to pasture on some hill country (Marden, 2004). This is because the roots of grasses are not able to hold the soil adequately against gravity. Furthermore, because soil dries out more under grass cover than forest cover, fractures form that accelerate erosion by allowing water to percolate through the soil and then seep along the more impervious surfaces, where lubrication occurs, leading to less frictional resistance and greater likelihood of movement (Grange and Gibbs, 1948). The result is erosion that causes significant thinning of topsoil depth, loss of nutrients and moisture holding capacity, with a substantial decline in pasture productivity (Hocking, 2006a).

The well understood issue is that "the absence of a forest canopy and lack of a dense network of intertwining roots in the subsoil is directly related to today’s accelerated rates of earth flow movement on pastoral hill country" (Marden, 2012). However, understanding the issue is one thing, but what is done about it is another.

Erosion and pastoral farming

Removal of indigenous forest cover in hill country and replacing this with a pastoral land use has increased the risk of earth flow initiation (Marden, 2012). There is a strong case for afforestation of erodible hill country currently under pastoral cover. However, can forestry and farming co-exist? Nordmeyer (1978) suggested in 1978 that "we have sufficient information now that, putting aside any entrenched views of land use and classic ways of land management, we can integrate farming and forestry to maintain and improve the land resource for future generations". However, Hocking (2006a) suggested that the reason why between two and five million hectares of erosion-prone hill country, that should be in forest cover, still remains in pasture, is that "our hill country farmers are just not interested in trees and sustainability". This despite minimal reductions required in stock carrying capacity of hill country farms, by only planting the highly erodible country in trees (Hocking, 2006a).

Hocking (2006a) also questioned whether soil conservation should be the sole responsibility of the landowner or a shared public responsibility. Before the 2017 general election and since the mid-1980's Central Government has not invested in forestry; and at that time responsibility for public benefits such as erosion control and watershed protection were also devolved to regional authorities (Moore, 2017). Hocking (2006a) suggested there is an opportunity for the crown to fund soil conservation plantings as joint ventures and share proceeds with the landowner. However, selective afforestation "requires knowledge, motivation and finance" (Gordon, 2014a). In addition a well-funded education programme, extension activities and technology transfer are all prerequisites to improving our current unsustainable pastoral practices (Hocking, 2006a). In an ideal world the "billion trees by 2027" programme would have a history of research and development supporting it.

While demand and market prices for eroding pastoral land are held artificially high as a result of externalities and do not reflect the lands productive capacity, subsidies are required to encourage planting in forest cover (Moore, H. 2014). Artificially high land prices also force landowners to stretch biological limits beyond reasonable bounds and increase grazing intensity at the expense of environmental outcomes (Moore, 2016). By regulating discharges into water and air, Central Government could influence land use change in favour of afforestation (Moore, 2017). Trading in discharge allowances such as via the Emissions Trading Scheme (ETS) also offers land owners an income stream that substitutes for lost pastoral earnings (Moore, 2017).

Both the positive and negative effects of a land use should influence decisions on economic value and choice of land use. The basis for making decisions on economic value should reflect the true costs and benefits of ecosystem services associated with land use (Harnett and Yao, 2015). However, the contribution that forests make to reducing erosion and sedimentation are currently undervalued in New Zealand (Parker, 2016). Given that farm productivity on steep hill country is severely affected by erosion, and afforestation is effective in reducing soil losses, ecosystem services provided by forestry (e.g. retaining soil capital, restoring water quality, improving in-stream habitat, reducing flood severity and resultant damage to infrastructure) should be a key driver in land-use decisions. However, to justify implementing soil conservation measures would require economic analysis quantifying the true costs and effects of erosion, such as lost productivity and expenditures on containing, repairing and living with erosion (Jones et al. 2008).

For an improved understanding of the beneficial role that forestry provides to New Zealand's economy and environment, Phillips et al. (2015a) suggested that modelling of slope stability, species selection and economics is required. This would link tree species to site characteristics for a better understanding of the trade-offs between ecosystem services and economic outcomes. In addition, by recognising and then actively managing the risk of negative effects resulting from forestry activities, the forest industry could both actively mitigate those risks while at the same time publicise that consequences such as wood on beaches, slips on roads and sediment in waterways are all being managed as best they can (Phillips et al. 2015a).

By plugging the information-decision gap, Eyles (2014) suggested a new approach could emerge that integrates forestry and agriculture together as sustainable land management, for a mosaic of pasture and trees according to land capability (Eyles, 2014). Realising such a vision would require training of land managers and regionally-based forest advisors (Eyles, 2014), which aligns well with Moore's (2017) vision of a climate change future that "looks like an extended mosaic landscape where pastoral farming, cropping and forestry co-exist" (Moore, 2017).

The need to address air and water emissions at a national level offers the opportunity for implementing large scale afforestation as the most effective and lowest cost solution to the issue of erosion, requiring planting of 30,000 hectares of grassland per year over the next 30-50 years (Moore, 2017).

Steeplands are very likely to receive the highest attention because of low pastoral productivity and high risk of erosion. Regulatory encouragement for afforestation (exotic or indigenous) could be in the form of an improved emissions trading scheme that actually encourages behaviour change; or even-handed nitrate discharge allowances (Moore, 2017). Such actions would encourage farmers to retire pasture and plant trees for income, or alternatively promote reversion to an indigenous forest in steep and remote areas not suitable for harvest (Moore, 2017).

Forestry for erosion control

In 2010 central government policy was that "the use of forests for controlling or reducing the impacts of rain events on erosion-susceptible land has and will continue to be important in many regions of New Zealand. Forests continue to be actively promoted as an erosion mitigation tool integral to many sustainable land management programmes" (Ministry of Agriculture and Forestry 2010b as cited in Phillips et al. 2012).

The use of woody vegetation is an effective method for both prevention of erosion on erodible country and rehabilitation of eroded country, becoming increasingly effective over time (Van Kraayenoord and Hathaway, 1986). Although forest cover does not necessarily provide total protection of the soil where erosion risk is severe, mitigating erosion with forest cover has been well researched and reviewed in New Zealand with the conclusion that forest cover significantly reduces sediment yields and that soil can be protected from erosion, provided sufficient trees are planted (Blaschke et al. 2008). Forest can also protect against gully development and accelerate gully stabilisation (Scion, 2012).

Grange and Gibbs (1948) described vegetation cover as the most important factor related to soil erosion, followed by rainfall, slope, parent material and then soil type. Since then numerous studies have come to the same conclusion, and that closed forest cover "reduces soil erosion on unstable slopes by around

90% compared to pasture cover" (Hocking, 2006a; Basher et al. 2016a).

There are a number of mechanisms that explain how trees and forests reduce soil erosion:

1. Dense vegetation or a forest canopy absorbs the force of rainfall impact, protecting the soil surface from surface erosion (Van Kraayenoord and Hathaway, 1986; Hocking 2006a);
2. The canopy intercepts rainfall which is then removed by evaporation, reducing water yield (Fahey and Payne, 2017). Water flow from a mature pine plantation can be 30% less than for pastoral farming (Quinn, 2005) with peak flows reduced by up to 50% (Fahey et al. 2004);
3. Trees reduce excess moisture in the soil by transpiration (Hocking 2006a) and this reduces pore water pressures (Ekanayake et al. as cited in Phillips et al. 2017), reducing the risk of erosion occurring;
4. Most importantly, tree roots provide mechanical reinforcement of the soil (Ekanayake et al. 1997; Hocking, 2006a). Reinforcement of soil by roots is achieved by their tensile strength (O'Loughlin and Watson, 1979), along with frictional resistance and soil bonding properties, which together are influenced by tree density stocking, tree size, tree species and soil physical characteristics (McIvor et al. 2011).
5. Grafting, or the interlocking of roots between adjacent trees can form a raft that forms a reinforced, semi-rigid layer that enhances mechanical reinforcement of the soil (Marden, 2012).

Plantation forest cover also reduces nutrient levels in both ground water and surface runoff when compared with pastoral land use (Quinn, 2005; Hock et al. 2009). The improved water quality delivered off-site from forest cover (Parkyn et al. 2006) is attributable to less soil erosion, less streambank erosion and less surface runoff (Quinn, 2005). Pine plantations also export much less nutrient than pasture because of the uptake and retention of nutrients by trees, along with their low fertiliser requirements (Quinn, 2005).

However, forests are also at risk of erosion, in particular during the period of time after clearfell harvesting and until the replacement forest becomes well established, a period known as the "window of vulnerability" (Phillips et al. 2012). It is during this period (and only if extreme rainfall events were to occur during this time) that plantation forests established on erosion-susceptible steeplands for the original purpose of stabilising these slopes, are particularly vulnerable to the initiation of landslides, which in turn mobilise slash and debris from those slopes and deposits it in stream channels. On-site consequences of landslide initiation include an increase in erosion while increased sediment yield, when combined with excessive slash in the form of a debris flow, can result in severe off-site consequences.

Plantation Forestry and Erosion

Forestry and Erosion Risk

Heavy rainfall events trigger erosion (Bloomberg et al. 2011). Duration and frequency of intense rainfall events are key factors that trigger mass-movement and gully erosion, the two most important forms of erosion in steepland plantation forests (Bloomberg et al. 2011). Slope is an important determinant for erosion risk and slopes over 32° depend on root reinforcement by trees for stability (O'Loughlin, 2005). Saturated conditions caused by heavy rainfall increases risk of slope failure and that risk becomes higher in high rainfall zones where annual rainfall exceeds 1500 mm (Bloomberg et al. 2011). Landslides "tend to initiate in slope hollows or depressions where subsurface drainage converges to produce high soil pore water pressures during heavy rainfall" (Sidle et al. as cited in O'Loughlin, 2005) and landslides are a significant contributor of sediment to water courses, even in forested settings (O'Loughlin, 2005). Shallow failures or slips tend to be a feature of steeper, concave slopes, and are usually concentrated on upper, steeper slopes (O'Loughlin, 2005).

The level with which erosion risk is mitigated from plantation forest cover depends primarily on the rotation status of the forest. For example, young plantation forests less than 6 years old sustained similar levels of landslide damage to pastured hill slopes during Cyclone Bola in the East coast of the North Island, which was 16 times greater than for plantations with closed canopies (Marden et al. 2016). This is approximately 1/4 of the total rotation length without full site occupancy.

Only once there is full root site occupancy and canopy closure do forests protect soils from erosion, therefore periods of vulnerability are influenced by two key variables – rotation length and tree growth rate (Knowles, 2006). A longer rotation length decreases the period of vulnerability (as a percentage of the rotation), provided that after clearfelling it does not take too long for newly established trees to reach the basal area sufficient to control erosion (Knowles, 2006).

Roads, landings, quarries and skid trails associated with harvesting increase the risk of erosion by disturbing and exposing soil, along with altering natural drainage patterns (Bloomberg et al. (2011). However, it should be noted that when compared with sediment contributed by gullies and landslide events, the sediment load from harvesting operations tends to be small (Bloomberg et al. 2011).

The NES-PF and Erosion Susceptibility Classification (ESC)

Since 1991, under the Resource Management Act (RMA) regional and unitary councils have been responsible for managing activities that cause erosion. However, to operate efficiently, the forest industry desired a single set of nationwide rules that regulate forestry activities with environmental outcomes, so have actively facilitated the development of a National Environmental Standard for Plantation Forests (NES-PF), which came into force on 1 May 2018.

The MPI website has a range of consultation documents and background information available for NES-PF stakeholders.

The rules and regulations

Under the NES-PF, environment regulations apply to eight plantation forestry activities that could have environmental effects in commercial plantation forests larger than 1 hectare:

- afforestation (planting new forest)
- pruning and thinning-to-waste (selective felling of trees where the felled trees remain on site)
- earthworks
- river crossings

- forestry quarrying (extraction of rock, sand, or gravel within a plantation forest or for operation of a forest on adjacent land)
- harvesting
- mechanical land preparation
- replanting.

Resource consents will be required where potential adverse effects would be significant or are not avoidable.

Erosion susceptibility classification

The NES-PF required a tool that took into account "the risks of erosion, sedimentation and environmental harm associated with plantation forestry activities in each of the classification zones" (MfE, 2011 as cited in MPI, 2017). By combining erosion severity potential identified in the New Zealand Land Resource Inventory (NZLRI) and the Land Use Capability (LUC) database, along with climatic data, a database and tool that maps classes of risk, called the ***Erosion Susceptibility Classification (ESC) May 2017*** was produced for the NES-PF. This tool supports councils and foresters in decisions on the level of risk associated with the NES.
See the Erosion Susceptibility Classification tool here»

The ESC divides the New Zealand landscape into 4 erosion categories that are colour coded according to risk. These form the basis for determining whether a plantation forestry activity:

- is permitted, subject to certain conditions being met, or
- requires resource consent because it's on higher-risk land.

Four zones are provided in the tool that each represent different levels of risk (see Figure 1). The categories are:

- Green (low) and yellow (moderate) — land less likely to erode. Plantation forestry activities are permitted.
- Orange (high risk) or red (very high risk) — land more likely to erode. Most forestry activities can't be carried out on red-zoned land without resource consent. Some activities, such as earthworks, also require consent on orange-zoned land with steeper slopes.

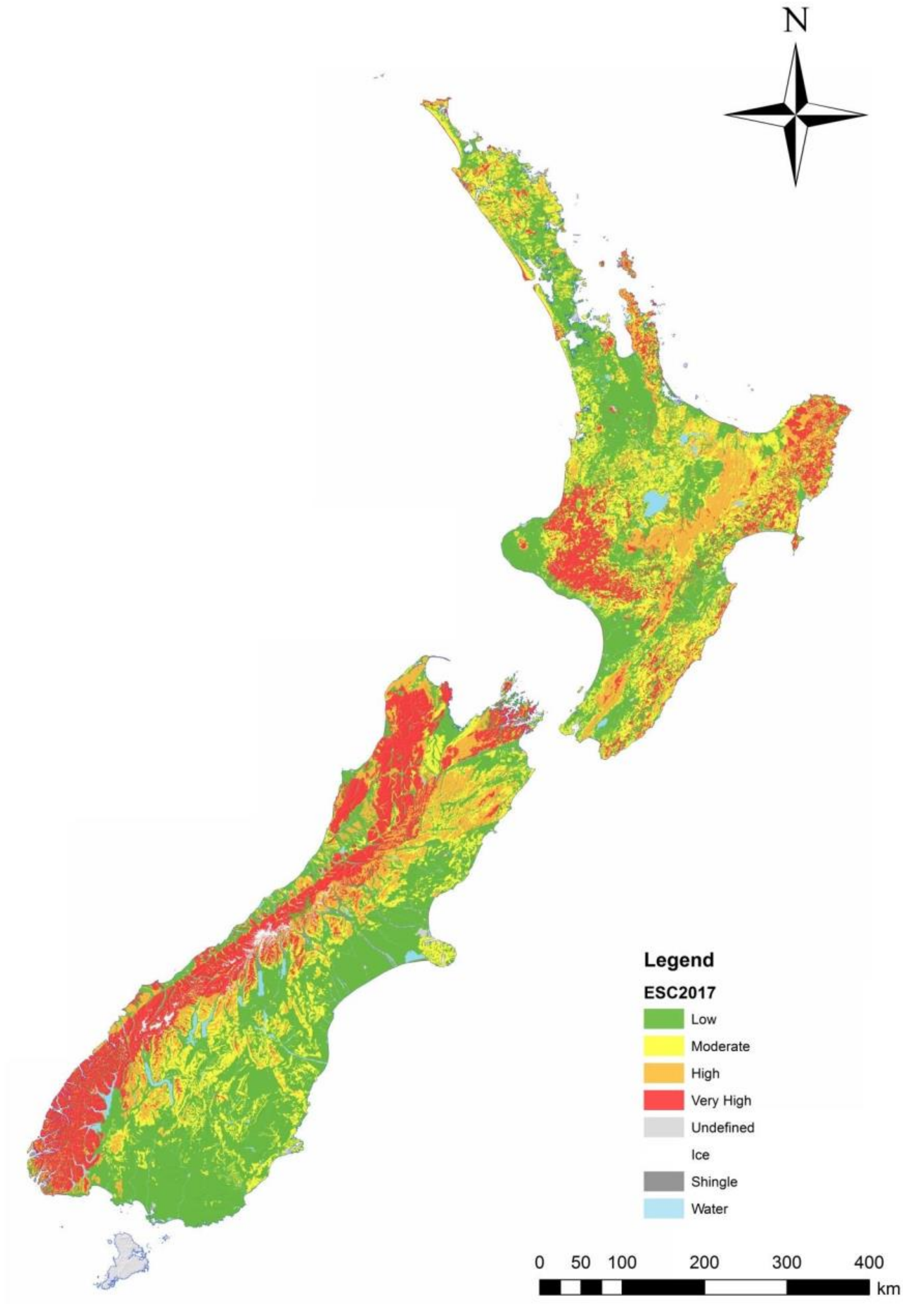

Figure 1: Erosion Susceptibility Classification

By identifying the susceptibility to erosion of the land unit in question, the ESC determines whether a plantation forestry activity is permitted, subject to certain conditions being met, or whether a resource consent is required because it's on higher-risk land. Consent may depend on conditional management practices that reduce the erosion risk above and beyond accepted levels of mitigation offered by standard forest management practices.

Potential improvements and research needs

MPI and MfE have published an overview of the NES-PF regulations stating:

> *For harvesting to be a permitted activity, foresters must submit a harvest plan to their local council if requested. The plan should identify environmental risks, including erosion susceptibility using the Erosion Susceptibility Classification tool, and must list the mitigations to be used to respond to those risks and achieve compliance with permitted activity conditions.*
> *Permitted activities are subject to conditions under the regulations that are based on industry good practice standards.*

Deficiencies identified with respect to the NES-PF include the need to develop an improved ESC:

- The term "erosion potential" is not well defined and is "based on subjective judgement and open to interpretation errors" (Phillips et al. 2017). Thus forest managers and territorial authorities require better tools for assessing risk at the site level. This might involve assessing the potential magnitude of erosion at the site level along with a risk assessment of likely on-site and off-site impacts and associated repair costs.
  In order to better evaluate the significance of sediment mobilisation under different forest management practices, an improved understanding of the conditions that trigger debris flows and landslides is required (Phillips et al. 2017).
- The scale of mapping is too coarse (1:50,000) for assessing erosion potential within a site (Phillips et al 2017).
- Probable misclassification of land (Phillips et al. 2017)

MPI have announced funding of high definition mapping of the Gisborne region to accurately assess erosion risks and better-inform erosion control decisions. This initiative intends to use LiDAR, a remote sensing tool that generates highly-accurate geographical terrain data, to assess erosion risks and assist in road design and planning. Improved management of natural hazards, such as areas of instability is a goal of this work but this would need to be undertaken at an appropriate scale in order to address inconsistencies in the ESC and improve risk assessment at the site level. Such hazard analysis is a priority for improving environmental performance and to better understand the erosion hazards associated with areas established in plantation forestry (Phillips et al. 2012).

Profiling risk as probability of landslide-causing storm events, then predicting the likelihood of failure at detailed scales and under different land management scenarios involves complex interactions between mechanical soil properties, slope, climatic factors, age of trees and individual species root network structures, that together are fraught with uncertainties (O'Loughlin, 2005). Whether this level of risk profiling for harvesting, planting and replanting on red-zoned land is necessary for the NES-PF is not clear.

Harvesting on red-zoned land (that is also LUC Class 8e) is a restricted discretionary activity where consent can be granted or declined, with consent conditions limited to the matters over which discretion is restricted. Replanting in red-zoned land after harvesting is a controlled activity, which means that consent conditions need to be reasonable and a resource consent must be granted. However, the regional council does have a level of regulatory oversight and control over the timing of the replanting and it may not be deemed appropriate to replant in exactly the same location as before, or a different species may be deemed better suited to the land slope and soil type. These decisions require judgement calls based on being well-informed on how well the proposed activity or the conditions being imposed mitigate the risk of erosion. In the short term, subjective judgement calls might be all that is available, but longer term acceptable practice might best be defined under the NES-PF.

The development of simple tools that correlate the likely frequency of landslide failure with quantitative data demonstrating the effectiveness of different erosion mitigation strategies (e.g. planting density, rotation length, species, mixed species forests with different rotation lengths etc) in reducing the erosion risk to an agreed sediment yield threshold would be useful to growers, managers and regional councils alike.

Perhaps a high level of accuracy is not required for mitigation measures that should be accepted by industry and the regulator alike as standard forestry practice for steepland plantation forestry. Conservative "best practice" erosion mitigation measures could even be described in a code of practice or standard for red-zoned land, or where necessary regulated. These practices might include:

- minimising mechanical soil disturbance when harvesting;
- high quality engineered earthworks and minimising length of roading infrastructure;
- minimising woody material left on slopes that have a high risk of failure;
- having buffers or planting setbacks between areas with a high risk of sediment mobilisation and water channels;
- ensuring rapid groundcover establishment after harvesting. This could be achieved by oversowing, immediately replanting and minimising vegetation dessication;
- replanting at a high tree stocking;
- Increasing rotation length;
- retiring excessively steep slopes inherently susceptible to landslides (e.g. > 35º) from production.

The level with which these mitigation activities should be practiced on red-zoned land could be agreed between industry and the regulator, with a track record developed that tests those practices and what they achieve over time. Measures could be fine-tuned as experience with them is improved. That is, consent for planting red-zoned land could be conditional on interim acceptance of their effectiveness at the site level.

Specific critical areas in most need of research should be addressed using forest grower levy funding. Areas identified in this report include:

- improve our knowledge of erosion mitigation provided by alternative species and regimes;
- methods to minimise slash mobilisation in debris flows from landslides;
- methods to retain debris flows so they do not reach water channels, such as tree buffers that retain landslide material;
- methods for utilising woody material to retain sediment and reduce risk of mobilisation;
- quantifying sediment retention from various types of buffers/setbacks that act as filters;
- improved establishment practices that rapidly initiate a vegetative cover after harvesting, noting that "establishment practices such as weed spraying, affect the generation, delivery, and ultimately the sediment leaving the forest." (Phillips et al. 2017);
- forest management practices that consider species and rotation length and quantify the benefits these offer in terms of erosion mitigation on steepland hill country;
- Options for transitioning unprofitable red-zoned areas to a permanent indigenous forest cover such as planted manuka, including an assessment of the duration of the window of vulnerability, potential long-term erosion mitigation effectiveness, and risk reduction as a comparison with radiata pine.

Forest harvesting and erosion

The forest canopy intercepts rainfall, reducing the quantity of water in peak flows, especially in small to medium intensity rainfall events (Fahey and Payne, 2017). Clearfell harvesting effectively eliminates evapo-transpiration, often resulting in saturated soils and increased subsurface water flow, thus increasing the risk of slip erosion (Elliot et al. 1999).

Loss of canopy from harvesting also exposes soil to direct raindrop impact and fluvial erosion (Jones et al. 2008). Tree removal allows soil to become wetter for longer (Pearce et al. 1987) and complete canopy removal by clearfell harvesting increases the risk of surface erosion and landsliding (Elliot et al. 1999; Marden et al. 2007).

Landsliding can generate large quantities of sediment and debris as a result of severe rainfall events and deliver this into streams, even in forested settings (Marden and Rowan, 1997; O'Loughlin, 2005). Shallow landslides can transform into debris flows and deliver large quantities of sediment and woody debris further down the catchment. Debris flows can also erode ephemeral gullies and riparian margins (Phillips et al. 2017).

Sheet and rill erosion resulting from earthworks, harvesting and land preparation can result in loss of soil and generation of sediment (Bloomberg et al. 2011). Although a relatively minor contributor of sediment into water channels compared with gullying and landsliding (Marden and Rowan, 1998; Marden et al. 2007), surface erosion or "slopewash" does tend to relocate sediment down-slope and can still be an important source of sediment delivery to streams, especially during severe storm events after harvesting (Marden and Rowan, 1997; Marden et al. 2002; Marden et al. 2007).

Logging systems that produce higher levels of soil disturbance and compaction produce higher levels of surface erosion, particularly in the first year after harvesting (Phillips et al. 2017). Sediment yields resulting from harvesting operations can be five times greater than pre-harvest rates, but do decline to pre-harvest levels within a few years after replant (Fahey et al. 2003; Phillips et al. 2017).

Under the NES-PF, sediment originating from harvesting must be managed to ensure that, after reasonable mixing, it does not give rise to any of the following effects in receiving waters:

- A conspicuous change in colour or visual clarity; or
- Rendering fresh water unsuitable for consumption by farm animals; or
- Significant adverse effect on aquatic life.

Soil disturbance

Surface soil horizons have the highest concentration of nutrients and greatest water-holding capacity, therefore surface soil disturbances generally reduce longer-term productivity (Elliot et al. 1999; Jurgensen et al, 1997). Under the NES-PF, stabilisation and containment of disturbed soil is required to minimise sediment entering water where it may result in certain adverse effects.

Soil disturbances are caused by wheeled and tracked harvesting machinery, by earthworks and by dragging logs across slopes. Mechanical disturbances to the groundcover remove organic material and soil litter to expose underlying mineral soil. This results in a substantial increase in slopewash generated sediment and sheet erosion (Elliot et al. 1999; Marden et al. 2006; Marden et al. 2007).

Level of sediment generation from slopewash tends to be proportional to area of soil disturbance generated from harvesting operations (Marden and Rowan, 1997; Marden et al. 2002; Marden et al. 2007). Sediment is mostly transferred from upper slopes to lower slopes, but mechanical site disturbance in proximity to streams greatly increases delivery of sediment to them (Marden et al. 2006). Where soil disturbances resulting from harvesting operations are deep, they can cause channelised flow that contributes sediment load to water courses (Marden et al. 2007; Bloomberg et al 2011).

Slopewash can be mitigated by measures such as:

- minimising soil disturbance and compaction;
- oversowing to accelerate repair of disturbances with vegetation cover that reduces the energy of the surface flow and binds soil particles in place;
- providing a riparian vegetation buffer that filters sediment (Marden et al. 2007).

Ground-based harvesting

Tracks required for skidder extraction result in substantial increases in sediment yields (Phillips et al. 2017). Ground-based clear felling operations also result in high levels of soil compaction that increase levels of fluvial erosion because soil porosity and drainage is reduced, especially when soils become saturated (Elliot et al. 1999). The area of mineral soil exposed by ground-based clear-felling operations may range from 21 – 66% (Bryan et al., 1985 as cited in Fransen 1998).

Cable hauler harvesting

Where disturbances are shallow, slopewash tends to not generate significant quantities of sediment because litter and groundcover reduces rainsplash and detachment of soil particles (Marden et al. 2006). However, deeper disturbances that expose mineral soil can comprise greater than 10% of hauler-logged cable settings (Marden and Rowan, 1997; Marden et al. 2006). These "deep" disturbances can continue to be a significant source of sediment for more than two years after logging (Marden and Rowan, 1997).

Greater depth of disturbance, especially where infiltration rates are reduced by compaction, increase sediment generation and mobility during the early post-harvesting period, especially in the first year (Marden and Rowan, 1997; Marden et al. 2007). This early period generates the most sediment because mechanical disturbance of litter exposes mineral soil to rainsplash, which detaches and mobilises soil particles (Marden et al. 2007). Without active intervention, vegetation tends to establish too slowly to reduce sediment production because newly colonising vegetation is undermined by raindrop impact and the exposed mineral soil has reduced moisture holding capacity (Marden and Rowan, 1997). Sediment generation can be greatest in the first three months after harvesting and during the first year can exceed that generated from harvest roads (Marden and Rowan, 1997). However, within one year sediment yields are significantly reduced as vegetation establishes (Marden and Rowan, 1997). After two years, in larger areas where exposed mineral soil is more deeply disturbed, vegetation recovery may only be partial, therefore they remain vulnerable to heavy rainfall events for longer (Marden and Rowan, 1997). However, the early re-colonisation process can be actively accelerated by oversowing (Marden et al. 2002; Marden et al. 2007).

Cable logging systems create fewer ruts than ground-based harvesting, covering less than 1% of the cutover area (Fransen et al. 1998). However, dragging stems across sideslopes does cause scarification of soil surfaces and haul paths from cable logging can result in soil disturbances that later form ruts (Marden and Rowan, 1997; Fransen et al. 1998; Marden et al. 2007). Sheet flow from soil disturbances can converge into rills that develop and enlarge during storm rainfall on freshly harvested ground to become ruts (Fransen et al. 1998; Marden et al. 2006). Although ruts can channel surface water runoff and convey soil material down the slope (Fransen et al. 1998), where these are generated from shallow disturbances, sediment tends to settle in micro-topographical hollows further down the slope rather than entering waterways (Bloomberg et al. 2011). Conversely, sediment generated within deeply scoured haul paths located in close proximity to stream channels generally enters waterways (Marden and Rowan, 1997).

The extent of deep soil disturbances caused by hauler logging can be reduced by:

- ensuring adequate log lift over as much of the haul length as possible;
- uphill-hauling logs away from stream channels rather than across them; and
- harvesting smaller areas so that fewer logs cross the same ground (Marden et al. 2007).

The NES-PF requires butt suspension ("suspending the sawn base of the tree being harvested above the ground or surface of a water body while pulling it to a landing”) wherever practicable. However, sufficient lift to keep logs off the ground is not always possible in some terrains. There is a trade-off between building more roads, tracks and landings that generate sediment, and greater levels of soil disturbance resulting from hauling in less than optimal conditions, where the logs get dragged across slopes (Marden et al. 2002).

Because deep scouring is rare in well-managed hauler logging operations (Fransen et al. 1998), harvesting with cable haulers may be the only option for steepland with fragile soils (Raymond, 2012). However, the cost of extraction is generally at least double that of mechanised ground-based systems (Raymond, 2012), an important consideration given that the proportion of forest best suited to hauler logging (i.e. slopes greater than 20 degrees) was 44% of the total area harvested in 2014, and is forecast to rise to 53% by 2016, and to over 60% by 2025. (Moore, H. 2014).

Earthworks

Forested catchments may yield up to 80% less sediment than pastured catchments (Phillips et al 2017). However, earthworks can generate large amounts of sediment by causing mass movement or surface erosion (Basher et al. 2016b). Such erosion-generated sediment can be controlled very effectively by "hard" engineering works that prevent sediment from being discharged off-site, or that prevent erosion from occurring by diverting water flow. Susceptibility to erosion from earthworks can be minimised by carefully designing drainage channels and roads to an engineered standard (Bloomberg et al. 2011). Engineering works can:

- reduce water velocity to manage runoff;
- modify slope hydrology to reduce mass movement erosion;
- trap sediment before it moves into waterways; and
- improve streambank strength to resist hydraulic scour (Basher et al. 2016b).

Export of sediment may be prevented through appropriate structures such as dams, silt traps or wetlands (McIvor, 2011) and careful siting of roads and landings (Basher et al. 2016b).

The forest industry has become very active in managing the environmental effects of earthworks by careful planning that ensures best-practice engineering design and construction practices. These practices have significantly reduced sediment yields from landing and road construction earthworks (Phillips et al. 2012). The Forest Owners Association have published the Code of Practice for Plantation Forestry (2007) and the Road Engineering Manual (2012), as guides to best management practice. However the contribution that infrastructure and clear cut forestry operations have on generation of sediment is not yet well characterised (Basher et al. 2016b).

Roading

Because roads inherently have low hydraulic conductivities, surface runoff creates a high risk of causing soil erosion if this is not managed (Elliot et al. 1999). Harvest roads and tracks are a major source of sediment supply to streams (O'Loughlin, 2005). That said, surface erosion of roads by fluvial action produces significantly less sediment yields than mass movement erosion, where this occurs (Bloomberg et al. 2011).

Sidecutting of steep slopes for roading decreases site stability - the cut side is likely to slip and the fill side may be too steep and fail as slumps, landslides or even avalanches (Bloomberg et al. 2011).

Harvest systems that require higher levels of road, track and landing construction generate greater levels of slope disturbance and inherently increase the potential for slope instability (Phillips et al. 2012).

Location of roads should recognise erosion hazard, such as avoiding unstable ground and locating roads on ridge tops terraces and benches (O'Loughlin, 2005) and use appropriate construction methods to prevent landslides (Phillips et al. 2012), including "catering for drainage, avoiding extensive side casting on steep slopes and vegetating new cut and fill slopes" (O'Loughlin, 2005).

As road age increases, the risk of erosion increases (Bloomberg et al. 2011). Therefore road maintenance should be undertaken at regular intervals to prevent high costs associated with remedial works.

Limiting harvest operations to periods of dry weather may allow harvest machinery access to a plantation area where roading standards are limited by cost, while also managing erosion risk (Palmer, 2013a).

Woody debris

Wood is an integral part of waterway ecosystems where it is transported down through the system, gradually breaking down from abrasion and decay, with some woody debris ending up in lakes, estuaries and coastlines (Ballie, 2005). Large woody debris, if well anchored in waterways, have a significant positive impact on the stream ecosystem. This impact is greatest in smaller waterways with lower flows because woody debris are less likely to be dislodged (Ballie, 2005). Anchored wood (Ballie, 2005):

- slows down water flow thus dissipating energy that could otherwise cause scouring and carry sediment downstream;
- helps aerate water and increase residence time, thus improving microbial decomposition of organic material;
- provides food resources and habitat for fauna.

However, because most of the larger pieces are removed at harvest, smaller logs and pieces that end up in the stream channel may not anchor well. Being so mobile, during high water flows this material may form debris flows and cause damage downstream, so removal of these from streams is common practice (Ballie, 2005).

Mobile sediment can be constrained by the presence of harvest debris (stem and branch material) by slowing down the velocity of water flowing overland (Marden and Rowan, 1997) so these have potential as a tool for actively mitigating post-harvest soil losses from entering streams. This could include positioning larger structural material to hold smaller material and sediment in place where sheet erosion occurs and in ephemeral channels and smaller more stable waterways (Ballie, 2005). Such active management would need to ensure that woody debris do not become mobilised and delivered into larger water channels during a severe storm event. Slash traps are a permitted activity under the NES-PF for the purpose of catching larger pieces of slash that would otherwise be flushed out of the catchment in high flow conditions (MPI, 2018). Design must allow water to flow freely through the slash trap, which must be maintained and reported on to the Regional Council annually, detailing frequency of maintenance and clearance along with condition and performance. This is to ensure large quantities of slash do not build up and become mobilised during heavy rainfall events (MPI, 2018).

Under the NES-PF slash and debris must be managed appropriately:

- Slash from harvesting must be placed onto stable ground;
- Slash from harvesting that is on the edge of landing sites must be managed to avoid the collapse of slash piles;
- Slash from harvesting must not be deposited into a water body or onto land with a high risk of flooding.

Debris flows

Landslide-generated sediment when mixed with woody debris can form a debris flow and if confined to a channel they become far more destructive than water alone (Scion, 2017).

Where slopes are steep and susceptible to mass failure, the risk of debris flows is increased (Scion, 2017). Debris flows are most likely to occur during intense rainfall events in the post-harvesting "window of vulnerability" period (Scion, 2017). Where there is slope failure with larger slash and log residues present, the destructiveness of debris flows increases, with negative consequences downstream as unwanted debris dams or the accumulation of material along coastlines or in lakes (Bloomberg et al. 2011). Debris flows also erode the water channel that carries them, so can carry large amounts of sediment downstream (Scion, 2017). Deposition of sediment then aggrades water channels, increasing the risk and severity of flooding events (Marden and Rowan, 1997).

Managing the occurrence of debris flows and minimising their impacts involves reducing the risk of landslide occurrence, by

1. reducing the duration of the window of vulnerability after harvesting; and
2. extending the rotation length (Scion, 2018).

Vegetation management

Vegetative cover enriches and protects soils from erosion. A strong regeneration of weeds after harvesting was found to be important in mitigating erosion (Fransen, 1998). Conversely, the desiccation of weeds that compete with or prevent rapid establishment of tree seedlings, or the application of residual herbicides that prevent vegetation from establishing, may facilitate surface erosion processes during storm events (Bloomberg et al. 2011). Because plant roots bind soil particles at the soil surface, rapidly reinstating a vegetative cover controls surface erosion and avoids undercutting and increases slope stability (Phillips et al 2012). The sooner vegetation cover recovers after harvest (in contrast to soil remaining fallow), the less soil is lost as surface erosion, especially from ruts and soil disturbances in the logged setting (Fransen, 1998). Undercutting of slopes by fluvial erosion in heavy rainfall events can even trigger landsliding (Phillips et al. 2012).

Weed control in radiata pine forests generally involves releasing trees by applying herbicides two or three times in the first few years (Ronaldo and Harnett, 2015). Although this practice of releasing young radiata pine from weed competition is well known to accelerate tree growth, weed competition can also have a beneficial effect on tree form, with fewer multiple leaders and malformations, less branchiness along with less toppling and sweep (Mead and Lucas, 2008). There may be an opportunity for steepland forest managers to explore the tradeoff between encouraging vegetation to establish rapidly on a recently harvested site to mitigate erosion, and limiting establishment of competing vegetation on the site for ease of tree establishment and early tree growth rates.

Forest Management and Erosion

"In the 1970s we anticipated that appropriate harvesting techniques for gully planting would be in place before harvest for small radiata plantings, but regretfully this has not happened. Until it does we need fast-establishing and slow-growing trees with quality wood which can be harvested in small lengths for niche markets" (May, 2017).

Erosion reduces forest productivity by reducing soil water availability, removing plant-available nutrients and degrading soil structure (Elliot et al. 1999). A range of harvest management options are available to assist forest managers in mitigating the risk of erosion. For example harvesting options include clearfelling (high risk), or single tree harvesting (low risk) thereby maintaining a permanent canopy cover.

Scale of the operation, the cost of access and the cost of harvesting are important considerations for managing steepland forest plantations, especially where the species is selected for production of lower value commodities (e.g. radiata pine). The steeper the terrain, the more difficult access becomes and the further from the port the less profitable the forest will become (Moore, 2015). Managing erosion may result in steeplands being under permanent forest cover and a change in species to one with a longer rotation and a higher timber value, or where uneconomic retiring the land from production with reversion to natural forest cover.

Also, the risk of windthrow is an important consideration in the selection of management and harvesting regimes. The likelihood of windthrow losses increases immediately following thinning (Somerville, 1980; Somerville, 1989), especially in clearfell systems with the goal of maximising volume and diameter within a time frame, whereby thinning may result in widely spaced trees with a high height to diameter ratio (Perry et al. 2015). Conversely, irregular forest structures such as those under a continuous cover, tend to have lower height to diameter ratios which could increase wind-firmness (Mason, 2002; Schelhaas, 2008).

Scale of operation

Reducing the cost of harvesting can significantly improve profitability and harvest production efficiency improves as harvest area increases (Raymond, 2012). Reducing cable logging costs for smaller harvest volumes is challenging (Raymond, 2012). Given that small-scale forests are less efficient to harvest, Moore (2015) suggested that one solution to improve cost-efficiency is for "small-scale forest owners to work collectively to maximise the profitability of these forests". However, where retrievable volumes are low, machinery costs will be high regardless of the size of the area being harvested.

Efforts in New Zealand to improve the efficiency of cable operations while also eliminating manual chainsaw felling have resulted in the successful use of excavators to fell and bunch logs on slopes (Raymond, 2012). Delimbing in the forest reduces stem weight, enabling extraction with smaller faster cable yarders, which "has led to increased adoption of mechanised harvesting on steep land, taking advantage of improved production, lower costs and improved safety" (Raymond, 2014).

Feller buncher machines have been developed in New Zealand that are capable of working on slopes in excess of 45 degrees. However, the large machinery as used in high production harvesting (i.e. bunching and grapple extraction) is not cost effective for small-scale harvesting operations, particularly where sites are scattered, because of the costs associated with relocating heavy machinery (Raymond, 2014).

Lightweight yarders with an operating weight of 45 tonnes and designed to work at a high production level can cost-effectively harvest smaller and steeper forests (e.g. Log Champ LC 550) and the excavator-based Harvestline yarder offers efficient log extraction in difficult, short to medium distance cable extraction areas, with a maximum effective haul distance of 350 m. However this requires expensive and heavy machinery (a 35 tonne plus excavator) which inevitably increases the harvesting costs, but has minimal environmental impact.

Skidder-mounted cable haulers with log extraction to a roadside log storage yard is another practical option for smaller-scale harvesting that avoids ground-based systems and can produce significant economic returns on challenging steep sites (Palmer, 2013a). Other options for small-scale steep slope harvesting include modern small-scale cable logging (skyline) systems such as the Maxwald mini skyline system (ForInco, 2016). The Maxwald mini skyline system requires greater than 17 degrees slope, has a maximum load of one tonne, and requires a extractable volumes of 30 m^3 per corridor (300 m maximum extraction distance) to be economically viable (ForInco, 2016).

Continuous cover forestry

Under the NES-PF harvesting is a permitted activity on red-zone land provided a 75% canopy cover is maintained at all times (low intensity harvesting).

Silvicultural systems that maintain the forest canopy and mimic natural successional processes are considered to be a more sustainable forest management practice than clearfell harvesting (Barton, 2005). Maintaining the complete forest cover offers improved soil and water values (Barton, 2005). Continuous cover forestry encompasses a range of practices from small coupe harvest removals to single tree extraction (Barton, 2005). In the United States clear-cut harvesting practices are being replaced by partial-cut harvesting under ecosystem management principles in an attempt to manage erosion (Elliot et al. 1999). However, limiting the size of clearfell coups presents both operational and economic challenges (Bloomberg et al. 2011).

Managing forests under continuous cover requires an intimate understanding of the site requirements of each species being considered (Barton, 2005). For example species requiring high light levels should be harvested in larger coupes. Larger coupes are considered to be no wider than two tree heights, thus limiting coupes to no more than a quarter of a hectare in area (Barton, 2005).

Although the approach is similar to the planting of an even-aged forest in a single species, greater attention is required in the siting of each species by understanding its ecological requirements, while also considering site soil quality and climatic conditions (Barton, 2006). For example exposed sites may require nurse crops or high initial stocking, fertiliser may be required for poorer soils, species must be selected according to soil moisture availability and unwanted regenerating species controlled (Barton, 2006). Forward planning might predetermine coupe size, stocking and rotation length for the forest to produce a continuous supply of logs of the desired volume and size range (Barton, 2006).

Forest improvement practices focus on individual trees and those stems with the best quality wood. Interventions that optimise returns consider individual tree regeneration and increment rather than clearfell considerations such as age and stand volume (Barton, 2005). This involves actively managing the forest for optimum productivity, with interventions such as timely thinning of poor quality trees and the removal of mature crop trees to ensure that the remaining trees have sufficient room to grow (Barton, 2006). Maintaining the vertical structure of the forest should aim for greater structural diversity, with "tiers" that improve longer-term productivity by allowing dominant trees to put on as much volume as possible, while also ensuring that subdominant trees are positioned to put on growth once the dominant trees have been removed (Barton, 2006).

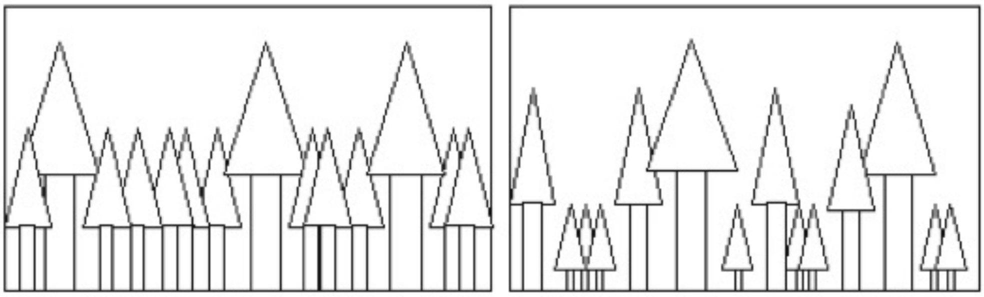

Figure 2: Diagram of two-aged and three-aged, multi-aged stands

Maximum stand density index (or basal area) for an even-aged stand requires that the target tree size increases as stocking decreases. That is, as target diameter increases, fewer trees can be grown in an even-age stand, therefore less use is being made of available growing space for volume production during the growth period. In contrast, multi-age management opens opportunities to harvest large target diameters and also maintain a high level of site occupancy, by increasing the frequency of harvesting operations and harvesting fewer trees each time (Berrill and O'Hara, 2007). Continuous cover methods practiced in California redwood stands involve predetermining the harvest cycle (time period between harvest operations) and setting target diameter, which then dictates number of trees harvested in each cycle (Berrill and O'Hara, 2007). With a single cutting cycle (i.e. two-aged stand, Figure 2), basal area may be reduced by up to 80% in a single harvesting operation (Berrill and O'Hara, 2007). Averaged over time, by increasing the frequency of cutting cycles, a greater forest cover is achieved

(Berrill and O'Hara, 2007). Productivity is maximised with individual cycle lengths as short as possible, while profitability is a tradeoff between higher harvesting costs for shorter harvesting cycles and maximising volumes harvested of high quality large diameter trees (Barton, 2006). Managing individual cycle lengths to be as short as possible also carries with it a greater risk of harvesting damage to the residual stand (Berrill and O'Hara, 2007), so management requires multiple trade-offs.

Maintaining records of the distribution of trees within size classes allows actual and desired proportions for each size class to be compared, with the objective of optimising stocking and maximising growth increment. Harvesting of trees is limited to those that have achieved the target diameter, thereby ensuring annual harvest volumes are maintained at or below the annual incremental increase in stem diameter (Barton, 2006).

Continuous cover forestry is more likely to be economically viable if the timber is of sufficiently high value to offset harvesting costs (Wallwork and Rapley, 2009). On steeper country where roading is impractical, helicopter extraction is an option that ensures minimal damage to soil, but to be economically viable this also requires timber values to be high (Barton, 2005). Although high value timber trees may remain economically viable despite the high cost of using more sensitive harvesting systems (May, 2017), it is worthwhile noting that “marketing of small quantities of logs is always a problem” (Van Kraayenoord and Hathaway, 1986).

Following harvesting, management practices should aim to encourage the growth of the residual stand. This may involve removing weeds and reducing tree stocking to an optimal stand density. Regular releasing should also be practiced (Barton, 2006).

Farm forester John Wardle practices continuous cover radiata plantation forestry near Oxford, Canterbury, using a single tree selection system called target diameter harvesting (TDH). Single trees are harvested with the target diameter (DBH) being 60 cm, with consideration also given to tree form, gap creation and spacing of residual trees (Sharland, 2008). However, "Very precise controlled directional felling is essential to prevent damage to the residual crop and to protect existing regeneration" (Sharland, 2008). Trimming, log making and cross cutting all take place at the stump, with logs skiddered to a mini-landing before being transported off site (Sharland, 2008). An economic evaluation of Wardles "Target Diameter Harvesting" (TDH) system concluded that similar returns to those achieved for clearfell harvesting were possible, but with improved ecosystem services (Perry et al. 2015). Harvesting only 15 trees/ha/yr^{-1} produces 40-50 m^3 of logs, with returns of $1300/ha/$yr^{-1}$ in perpetuity, with thinning getting a growth response even in large trees (J. Wardle, pers. comm). Through a pioneering process of adaptive management Wardle is increasing tree densities per hectare and carrying larger standing volumes (J. Wardle, pers. comm).

A project is currently assessing the practical requirements and constraints of introducing the TDH system to forests of different sizes, along with the economic feasibility of such systems (NZFFA, 2018).

Spaced tree plantings

Space-planted trees are a widespread method used by hill-country pastoral farmers to control erosion. Tree species planted are usually poplars and willows, but other species such as Eucalyptus and Acacia are occasionally used (Basher et al, 2016b). However, no studies have measured their effectiveness under differing severity of storm events, nor on sediment yield (Douglas et al. 2009, as cited in Basher et al. 2016a).

The success of space-planted trees in controlling landslide erosion depends both on good initial establishment of the trees, along with subsequent maintenance to ensure good root and canopy development (Basher et al. 2016a). Increased tree size and planting density both reduce risk for landslide erosion to occur, but there has been limited work quantifying these relationships (Basher et al. 2016a). These limited studies suggest that only once mature, do trees planted at wide spacings significantly reduce landsliding, and then only within a distance of 10 m from the trees. Younger and smaller space-planted trees offer little protection and are only effective once diameters reach 20-30 cm (Basher et al. 2016b). The interaction between roots of neighbouring trees is a major factor determining success of close tree spacing in preventing erosion and therefore levels of erosion reduction attained by space planted trees are nowhere near the level attained by forest cover (Basher et al. 2016a). Although a clear improvement over having no trees at all, sparse tree cover and a long window of vulnerability that is dependent on tree spacing and size offer limited mitigation benefits.

Agroforestry and tree stocking

In converting pastoral land to forestry, grazing can be retained between trees for a period of time. By decreasing initial tree stockings and retaining lower residual stockings, pastoral productivity is retained for longer. With a low final crop stocking of 200 stems per hectare, grazing is available for half the rotation, but productivity is halved during that time (Mead and Lucas, 2008). Agroforestry (i.e. low tree stockings) on steep slopes is therefore a trade-off between risk of erosion, pastoral productivity and poor wood quality resulting from heavily-branched trees that also reduce returns because of high harvesting costs.

Toppling is a considerable risk for low-stocked stands in that gaps in the canopy both increase erosion risk and also reduce productivity. Physiologically aged cuttings can result in lower levels of toppling compared with seedlings (Mead and Lucas, 2008; Moore, J. 2014).

On fertile pastoral sites a low tree stocking to retain grazing results in large logs and a shortened rotation (Hawke, 2011). However, the trade-off for the fast diameter growth rates produced by individual trees under low stocked regimes is a low total harvest volume and with low value branchy headlogs (Hawke, 2011), which can produce poor returns (Jones and Cullen, 2008). Mason (2007) and Hawke (2011) explained the trade-off between volume and value, whereby low stocking rates increase volume of pruned buttlogs at the expense of total volume. Hawke (2011) found that top breakages and poor stem straightness were both prevalent in low-stocked stands, whereas stands with higher tree stockings were largely unaffected. Seymour (2017), on the other hand, produced good returns from 25 year old hill country radiata planted at a stocking of 150 stems per hectare, by using improved cutting grown stock and high pruning to 8.5 metres in five regular and well-timed lifts, to retain a small DOS and maximise clearwood recovery and buttlog volume. Nevertheless, larger trees with heavier branches do challenge the cost-efficiency of mechanised harvesting systems (Raymond, 2012).

Agroforestry at low tree stockings, especially where soil conditions are good, produces fast diameter growth that results in large branches and also poor wood stiffness, limiting use for structural framing applications (Bawden, 2007). In contrast, full site occupancy produces slower diameter growth (closer growth rings) and greater wood stiffness (Bawden, 2007; Hawke, 2011). Mason (2007) also found that wood stiffness improves by increasing between-tree competition. Therefore, production of better structural timber grades from headlogs, along with large diameter pruned buttlogs, while also mitigating erosion risk on steep slopes, would require high initial stockings to minimise the volume of juvenile wood, with a progressive series of thinnings each time full site occupancy is achieved.

Bawden (2007) also suggested that because steeper slopes tend to have less soil moisture and nutrients available to trees, wood properties such as density and stiffness are improved because of the resulting slower growth and longer rotation length. Longer rotations also reduce erosion risk and once age exceeds 30 years, radiata wood tends to have improved stiffness properties (Bawden, 2007). Longer rotations are also preferred by log buyers but do come at an economic cost (Mason, 2007).

As tree stocking increases, a greater volume of wood is produced per hectare (Hawke, 2011). With no thinning and at planted spacings of 6 m x 6 m good returns were reported for high pruned radiata harvested at 26 years old, with 78% of net returns coming from pruned logs (Mackenzie, 2017). Moore and Harnett (2016) reported that a final crop stocking of between

400 and 600 stems achieves the greatest standing volume per hectare and that stocking rate is the key determinant for value.

Prices for different log grades also tends to influence management decisions on tree stocking and silviculture. Improved seedlots produce trees with better branch architecture and improved stem straightness, and therefore improved log grades and greater returns (Moore and Harnett, 2016). However, as seedlots are improved for growth and form, deploying these at lower stockings has the potential for increasing erosion risk on steep hill country.

Managing post-harvest landslide risk

Although tree roots reinforce the soil and prevent erosion, the tree canopy also makes the soil drier which increases soil strength (Marden et al. 2016). When the trees are removed, the soil is directly exposed to rain and therefore surface erosion, but also to increased water infiltration, which increases risk of landslides occurrence. Then, as tree roots decay, their soil reinforcement capacity is lost. Although mature plantation forests control erosion very well, there is a period of between two and eight years following harvest where slopes are vulnerable to erosion (Phillips et al. 2012 as cited in Basher et al. 2016b). This is known as the "window of vulnerability", which has a significant influence on the risk and magnitude of damage caused by storm-induced landslides (Marden et al. 2016).

Until trees achieve full root occupancy and canopy closure occurs, erodible slopes remain vulnerable to landslides (Marden et al. 2016). Radiata pine plantations less than 6 years old and planted at moderate stockings do not have sufficient site occupancy to reduce erosion (Marden, 2004).

In addition to rotation length, harvesting methods and silvicultural practices (in particular planting tree density and tree growth rate) also influence the risk profile for post-harvest erosion to occur (Phillips et al. 2015a).

Harvest risk and the window of vulnerability

The period of maximum susceptibility to mass movement is between 2-8 years after clearfell harvesting (O'Loughlin, Sidle, Watson as cited in Phillips et al. 2012). See figure 3.

The risk of sheet erosion and rill erosion is greatest immediately after harvesting because of soil disturbance and removal of forest cover.

Rotation status and level of canopy closure both influence the level with which erosion risk is mitigated: Factors that influence this include:

- A forest canopy intercepts rainfall and increases evaporation of moisture, resulting in lower soil water balances (Bloomberg et al., 2011; Basher et al. 2016b; Pearce et al. 1987).
- Tree root growth and resulting level of root reinforcement increases with age from planting. This is more important than canopy interception in terms of mitigating erosion (Sidle and Ochai 2006).
- Forest litter accumulation has soil building effects such as improved soil aggregate stability (Bloomberg et al., 2011 p 23) and increased hydraulic conductivity (Elliot et al. 1999) that mitigate erosion risk.

As stumps and roots decay, root reinforcement of soils is reduced (Basher et al. 2016b). Rapid development of a replacement stabilising root network is important for reducing risk of mass-movement erosion events. As root site occupancy increases with age of the replanted stand after clearfell, landslide risk reduces. However, the length of time between harvest and root decay is species dependent (Phillips et al. 2012). Radiata pine roots decay quickly and lose half their tensile strength within 15 months of harvesting (Watson et al. 1999), resulting in significantly reduced soil reinforcement. The new soil-stabilising root network in the replacement crop is likely to be slower to establish than the decay-induced loss of reinforcement resulting from harvesting (see Figure 3). Clearfell harvesting of radiata pine results in a period of time where risk of erosion is substantially increased (Watson et al. 1999). Post-harvest slope stability is therefore influenced by:

1. **tree stocking rate**
   Increased planting densities offers faster development of a stabilising root network; and
2. **tree species**
   A species with slower rate of root decay than radiata pine offers a longer time period before soil reinforcement is lost.

Replant stocking rate is also dependent on growth rate of the species planted because faster growth results in a shorter time period for recovery of root reinforcement (Phillips et al. 2012).

Because erosion of soil tends to reduce productivity over much longer time frames than a single rotation (Elliot et al. 1999), clearfell harvest frequency also influences the proportion of the harvest cycle that has insufficient root reinforcement prior to canopy closure (Bloomberg et al, 2011).

Species

The window of vulnerability occurs during the first 6-8 years of a typical radiata pine rotation (Phillips et al. 1990). Rate of decay for the roots of the removed trees also influences rate of root reinforcement loss (Phillips et al. 2015a). Once the stem is cut, radiata pine roots decay rapidly and lose their strength such that "within a few years little can be seen of the root system in the soil" (Watson et al. 1999 as cited in Phillips et al. 2012; see also O'Loughlin and Watson 1979).

Knowles (2006) concluded that radiata root strength has a "half life" of 15 months after harvesting, implying a progressive loss of root strength that halves again after 30 months. Kanuka roots, on the other hand, were estimated to decay at only half the rate of radiata pine roots (Watson et al. 1999). This suggests that rate of decay is strongly influenced by species.

For some species, the cut stem and root system does not die. For example redwood "retains both the physical stump that continues to act as a 'buttress' as well as its intact 'live' root system" (Phillips et al. 2012). Other genera that include coppicing species include *Eucalyptus*, *Acacia* and *Populus*. In terms of soil reinforcement and effectiveness at controlling erosion, because such root systems remain alive they continue to occupy the soil and reinforce it. (Phillips et al. 2012).

Root site occupancy

The number of years required after trees are planted and before protection is afforded against shallow landslides depends on species composition, spacing of trees and growth rates (Marden et al. 2016). The threshold that closes the window of vulnerability is in theory the point where roots of adjacent trees overlap, referred to as "100% root site occupancy" (Phillips et al. 2011). Canopy closure also occurs around this time (Phillips et al. 2015a). The length of time to reach that threshold is primarily determined by early growth rate of the species being planted and the planting density (Phillips et al. 2015a; Marden et al. 2016). Earliest protection is provided by full root site occupancy (root overlap) and canopy closure, i.e. species with the fastest growth rates or those planted at high densities (Marden et al. 2016; Phillips et al. 2015a).

For reliable landslide protection, tree species "that have wide environmental tolerances are also likely to be preferred over species that are less widely tolerant" (Phillips et al. 2015a). Radiata pine grows well throughout much of New Zealand and is easy to establish (Maclaren, 1993). However, wide tolerances do not necessarily mean better adaption to specific soil physical conditions such as poor drainage, low soil nutrient availability or shallow soil depth. Root system morphology is also closely associated with site factors (Phillips et al. 2015a) whereby different species adapt in different ways to such site factors. Species preferences and limitations are therefore important for successful establishment and capacity to prevent erosion.

Rate of root biomass production varies between species for individual trees of a given age (Basher et al. 2016a). For example, eight year old radiata at a stocking of 2000 stems per hectare has a similar level of landslide risk to kanuka of the same age with a stocking of 10,000 stems per hectare (Ekanayake et al. 1997). To compensate for its smaller roots at all stages of growth, kanuka requires higher stand densities (Ekanayake et al. 1997). Where stand densities are very high (between 15,000 and 25,000 trees), for the first eight years "kanuka would provide a better level of protection against the initiation of shallow landslides than stands of planted and managed *P. radiata*" (Ekanayake et al. 1997). Knowles (2006) also found that species with less root biomass tend to have greater tensile strength, whereby comparative soil holding ability should be similar for all species, provided above-ground biomass is equivalent. Therefore tree size and stocking may be much more important than species in terms of root reinforcement (Knowles, 2006).

Planting density/tree stocking

Because of cost constraints and an improved selection ratio of 3:1 resulting from breeding of genetically improved radiata seedlings, initial spacing for radiata pine has been reduced from 2,200 stems/ha^{-1} in the late 1920's to current planting stockings of between 800 stems and 1200 stems/ha^{-1} (Sutton, 2007). The Ministry of Forestry (1994) recommended a planting density of 1250 stems/ha^{-1} on eroding land classes in the East Coast. This recommendation was based on a site occupancy model that used time-series data of crown and root diameters according to age and planting density (Marden et al. 2016). However, because root diameters were not known for radiata less than 8 years old, growth rates for this critically important establishment period in terms of vulnerability were only estimated (Marden et al. 2016). Marden et al. (2016) sought to improve the time series database for younger trees and tested genetically improved radiata to see whether faster growth rates would provide earlier root reinforcement compared with less improved radiata planting stock (such as was available from the 1960's onwards). Total root length, root cross sectional area and canopy growth rate were not significantly larger for genetically improved (GF 28) trees compared with GF 16 radiata at age four, suggesting that genetically improved planting stock may not necessarily provide an opportunity to reduce stocking without increasing risk of erosion (Marden et al. 2016).

Quantifying root reinforcement provided by trees involves the interaction between tree size and tree spacing (Schwarz et al. 2016). Tree size is influenced by growth rates for different species, which in turn is influenced by site factors (Knowles, 2006). As trees grow, radiata pine produces on average 1.1 tonnes per hectare of root biomass per annum for the first 9 years of growth, which increases to 7-8 tonnes per hectare by age sixteen and 9-10 tonnes per hectare between sixteen and twenty-five years old (Watson and O'Loughlin, 1990). Risk of erosion decreases as tree biomass production increases (Ekanyake et al. 1997).

Knowles (2006) found a strong relationship between basal area and root reinforcement (soil holding ability), with "a minimum threshold of 30 tonnes of radiata pine root biomass per hectare". Thus tree stocking and tree size when combined as basal area represent total biomass (for example 12,000 trees at 5cm dbh or 90 stems at 45 cm dbh both produce Knowles's 30 tonnes per hectare risk threshold). Canopy closure for typical radiata occurs between 6 and 8 years after planting, at which time the root systems are sufficiently well developed to reinforce the soil and minimise risk of landsliding (Marden et al. 2016). However, Knowles's model may require refining to more accurately profile a risk basal area threshold during the key establishment period when soils are most vulnerable and when thinning operations are undertaken, given that both initial tree stocking and thinning operations both affect canopy and root network areas (Bloomberg et al. 2011). Marden et al. (2016) suggested that when radiata is thinned, usually between 5 and 8 years after planting, despite widening of the canopy gaps, root development should be sufficient such that slope stability is not compromised.

What is clear from the literature is that root reinforcement occurs more rapidly at a higher stand density and increases over time. Watson et al. (1999) estimated that replanting radiata at 1250 stems/ha^{-1} after clearfell on erodible steep slopes results in a period of 4.7 years where root reinforcement is reduced, increasing to 5.6 years where replant stocking is reduced to 800 stems per hectare. The question is therefore: How high should stocking be, given the risk profile for the land being planted?

Historical evidence shows that densely planted stands afford protection from storms earlier than stands planted at lower stocking rates (Marden et al. 2016). However, the trend towards lower stocking rates for radiata, such as 833 stems per hectare (because of improved establishment practices and planting stock) has been found to increase the period of vulnerability and risk of erosion on slopes. Where planted 2 m apart, the canopy of adjacent trees touched within three years, whereas where planted 4 m apart this did not occur until between six and seven years of age (Marden et al. 2016). Although root spread increased significantly for each year the trees grew and by year 4 had reached a maximum of 6.04 m from the stem, at 1250 stems per hectare (4 m x 2 m) only 20% of total root length overlapped with roots of adjacent trees (Marden et al. 2016). Importantly, Marden et al. (2016) considered that radiata at this stocking and age, even with the gains in growth from genetically improved planting stock, would not provide "lateral and/or vertical root development to prevent the initiation of shallow landslides should a major storm event coincide with this early growth period".

Thus the "duration of the window of vulnerability" that culminates with the decay of the root systems of harvested trees needs to be shorter than the time it takes for the new root network to attain full root occupancy and thereby maximise net root reinforcement. Decisions on stocking rates could therefore involve a cost benefit analysis by the landowner, which would also take into account the probability of a landslide-triggering event occurring during the period of time it takes for the new crop to achieve 100% root reinforcement (Bloomberg et al. 2011). Sites with a higher risk might require a higher initial stocking than is current standard practice.

Although the level of root reinforcement required to stabilise a specific slope depends primarily on mechanical soil properties and slope (Schwarz et al. 2016), a much improved understanding of landslide thresholds is required for a range of different storm profiles in order to more accurately assess risk for each site (Phillips et al. 2015a). Risk-based regional mapping that links forest slope reinforcement models with levels of erosion susceptibility could provide such a risk profile (Phillips et al. 2015a) and aid decisions on planting stockings.

Silvicultural regimes would also need to be altered for very high initial stockings, with a higher number of thinning interventions required to progressively lower the stocking to an appropriate level for the desired rotation length. Sutton (2007) reported historical experiments with high initial tree stocking and little active management to retain live branches resulted in an abundance of small black knots in the timber and small tree diameters. However, it should be noted that small black knots are not undesirable for non-appearance framing products and planting at a high stocking for small knots followed by progressive thinning does produce good log grades and sufficient stem diameters. Active management could potentially take advantage of a high initial stocking to reduce branch size and pruning costs. Cost-effective alternatives to chainsaw thinning trees include ringbarking, which may be suitable for multiple progressive thinning operations in highly stocked stands (Satchell, 2018).

Root metrics and young trees

Phillips et al. (2015b) concluded that deficiencies in knowledge for below-ground traits hampers the ability to predict what effects different types of vegetation have on slope stability and that improved root information is required for an improved understanding of how and when individual species control erosion and how effective they are at different planting densities (Phillips et al. 2015b). However, Phillips et al. (2015a; 2015b) acknowledged that obtaining information on root morphology is time consuming and expensive, especially for older trees. Knowles (2006), on the other hand, simply used above-ground biomass to represent soil reinforcement capacity because below-ground biomass tends to vary between species. Trees with less root biomass tend to have greater tensile strength, whereby comparative soil holding ability should be similar for all species (Knowles, 2006). Poplar and Douglas fir are species that have less root mass but higher tensile strength, which results in similar levels of protection per tree provided above-ground biomass is similar. (Hocking, 2006a).

Root distribution is highly dependent on local environmental conditions (Schwarz et al. 2016) such as "soil physical conditions, particularly stoniness, site and soil drainage conditions, depth to water table, bedrock conditions and the strength and permeability of strata" (Phillips et al. 2015a). Tree growth is also dependent on soil fertility and climatic conditions.

Root spread, root depth and total root length are useful metrics for predicting comparative soil reinforcement performance by species (Stokes et al. 2009; Phillips et al. 2011, 2013a, 2014, 2015b). Marden et al. (2016) considered root size, biomass, lateral spread, depth, cross-sectional area and the strength of individual live, dead and decaying roots to be the relevant below-ground metrics useful for determining soil reinforcement by roots according to tree species.

Phillips et al. (2012) raised the issue that there is no "standard" for describing structural roots and defined structural roots as being those with a diameter greater than 1 mm, because this size class is dominant and abundant in young redwood and radiata trees. However, previous studies had mostly defined roots with a diameter of greater than 2 mm as "structural", thereby limiting comparisons but also creating a new and useful metric, "total structural root length" (Phillips et al. 2012). However, Marden et al. (2016) used greater than 2 mm diameter when measuring total root length for 1-4 year old radiata pine. Clearly there needs to be greater consistency between studies when comparing roots of different species, given species differences in tensile strength and below-ground biomass. For example, roots in young redwood are finer and more numerous than radiata, which has fewer, thicker roots at corresponding distances from the stem (M. Schwarz pers. comm. as cited in Phillips et al. 2012). Also, species with "deeper and more complex woody root networks impart better protection against shallow landsliding than shallow rooting systems, though in some cases dense networks of shallow woody roots can create a reinforced membrane of lateral-acting strength that may hold the underlying soil in place" (Sidle et al. 1985 as cited in Phillips et al. 2012).

Root systems create both lateral and vertical soil reinforcement (Phillips et al. 2015a). Different species have different methods for reinforcing the soil, for example radiata pine quickly develops vertical taproots and sinker roots (Marden et al. 2016) whereas redwood produces mostly lateral roots (Meason et al. 2012). Although roots were found to be more numerous and total root length significantly greater for young redwood trees compared to radiata, "the below-ground biomass for a given root collar diameter showed no statistical difference between the two species" (Phillips et al. 2012). Despite young redwood trees having greater total root length than radiata (Phillips et al. 2013, 2015a), root collar diameter appears to be the more useful metric for determining soil reinforcement.

Root collar diameter is useful for inferring root and below-ground biomass in young trees, as a proxy for DBH which is not a reliable measurement for size in young trees (Phillips et al. 2012). There is a significant relationship between root collar diameter and below ground biomass, meaning that below ground biomass and root biomass can be estimated by measuring root collar diameter independently of species (Phillips et al. 2012; Marden et al. 2016).

Root collar diameter increases exponentially in size in radiata pine over the first four years (Marden et al. 2016), suggesting that the window of vulnerability increasingly closes as trees grow. In the period between four and eight years of age, radiata produces significantly more vertical roots, both structural roots below the root collar but also sinker roots growing from lateral roots (Marden et al. 2016). Within that four to eight year growth period, radiata biomass increases by 75% and radial roots extend an additional 2 m from the stem (Marden et al. 2016).

Marden et al. (2016) found that "92% of the root mass of 4-year-old radiata was located within a 0.5 m radius of the root bole" with multiple vertical structural roots located directly below the root bole along with sinker roots that developed from lateral roots reaching the same depth as the vertical structural roots (Marden et al. 2016). Root depth increased from a mean maximum of 0.96 m in year one to 2.81 m after four years (Marden et al. 2016). However, by year four only 4% of total below-ground biomass occurred below 1 m depth (Marden et al. 2016). Where soils were deep and did not impede root development, vertical roots grew rapidly whereas thin soils and the presence of bedrock limited development of vertical roots and root biomass (Marden et al. 2016).

Comparative data was measured by Phillips et al. (2015b) from three year old trees for several species considered to have potential for controlling erosion. This study showed considerable differences in root systems between species at age three, suggesting greater potential for erosion control in some species. For example alder had the greatest overall root length and below ground biomass along with significantly deeper roots than the other species, with a rapid root spread with dense branching lateral roots and a high root density, suggesting it is a species very well suited to erosion control (Phillips et al. 2015a; 2015b). Blackwood had the greatest root spread and cypress had the greatest above ground biomass, following closely behind alder in greatest total root length (Phillips et al. 2015b). At age three, cypress had over three times the total root length of radiata pine (Phillips et al. 2015b). Beyond general observations, it is not yet known whether such differences in root system morphology are as important as root biomass, or whether root biomass or soil reinforcement can be reliably predicted from above ground biomass. Certainly early growth rates did vary considerably between species but "it is accepted that real differences between species are unlikely to emerge until the plants are considerably older – at least beyond 4 years from planting" (Phillips et al. 2015b).

Based on the wide range of root morphologies for young trees of different species, Phillips et al. (2015b) suggested that root reinforcement capacity could be inferred from measuring lateral root spread or total root length from three year old trees (Phillips et al. 2015b). Root measurements taken by Phillips et al. (2015b) showed that both redwood and radiata at age three "have greater than 50% of their total root length within 1m of the stem and show a rapid linear decline in total root length with radial distance" from stem, whereas blackwood and alder had less than 40% of the total root length within 1m of the stem with "a pattern of increasing total root length with distance from the stem to a maximum at about 1.5–2.0 m and then declining". Such metrics could potentially be used for modelling length of time required at a specific planting density for achieving 100% root site occupancy. However, exactly what metrics have the greatest influence over soil reinforcement is yet to be determined.

Tree Species

To control erosion on slopes "the need is for trees, not necessarily radiata pine." (Hocking, 2006a). Species preference can sometimes be from personal foresight, sometimes aesthetic considerations and sometimes economic drivers. Preference may also be driven by management choices and soil reinforcement performance that offers a reduced risk for erosion events to occur.

Species selection

The ideal tree species for erosion mitigation on hillslopes has the following traits (Clinton et al. 2009):

- Tolerance to New Zealand's soils and climatic conditions;
- Easy to establish;
- An extensive root system that can tolerate wet conditions and even burial in aggraded gullies;
- Capable of regenerating or coppicing freely.
- Long lived.
- No potential to become a pest.
- Production of high-quality timber of sufficient value that could be partially harvested.

Canopy growth rates, degree of canopy closure, along with root strength and root growth rates all determine the individual tree species suitability for controlling mass movement erosion. If alternatives to radiata were available that had similar growth rates but were suited to longer rotation lengths and had the ability to coppice, these could be promoted for improved erosion control forestry plantations (Phillips et al. 2012).

Radiata pine has the advantage of rapid early growth rates that offer good root reinforcement of soils by the age of 8-10 years (O'Loughlin, 2005). However, the traditional regime of clearfelling at 25 to 30 years old is not optimal for long term stability of sensitive slopes (O'Loughlin, 2005). Longer rotation lengths result in less frequent erosion.

Being the most studied plantation forest species in New Zealand, radiata pine provides a benchmark with which to compare performance of other species in terms of controlling erosion (Phillips et al. 2015a). However, even for radiata pine there is a limited understanding of structural root system development under different soil types and climatic zones (Phillips et al. 2015a).

Radiata pine, being the dominant plantation forestry species with well developed log markets and a long history of research and development, could be seen as the clear choice for steepland afforestation. Breeding programmes have produced a 30% increase in recoverable volume over the last 50 years (Moore, 2017) and most production forest companies in New Zealand only have experience with radiata pine. Phillips et al. (2015) suggested that radiata at standard-practice clearfell rotation length and planting densities may not be the appropriate species for erosion-prone terrain where there is a high risk of storm-induced landslides and asked if we could do better in terms of the window of vulnerability. In some cases such as where it is difficult to extract trees or where storm damage history suggests that erosion risk is too high for standard practice re-establishment, decisions about what to do next might need to take into consideration the option of changing species or tactical withdrawal and reversion (Phillips et al. 2015a). Consideration of the 'window of vulnerability' is key to such decisions (Phillips et al. 2015a), and this varies with species.

Biological risk is an important factor to consider in the selection of plantation forest species. The high up-front costs of establishing plantation forests and the long rotation lengths give rise to considerable investment risk. The plantation forest industry, being one of the largest primary industry sectors, is currently considering an industry levy in order to be able to meet costs of responding to any incursion that threatens the industry. The level to which industry would fund incursions on "alternative" species to radiata pine is open to speculation, but such a levy would primarily be collected from radiata growers.

Interplanting

Radiata pine and Douglas fir are produced in bulk, therefore seedlings are likely to be lower cost than "alternative" species. In order to keep tree stocking up and costs down, growers may wish to interplant their selected species with radiata or Douglas fir, which would be culled later. Because of the vigour of radiata, it is not generally recommended as a nurse for other species because it tends to overshadow them before they are well enough established and old enough to be released. Douglas fir, on the other hand, makes a good nurse crop for most species listed in this report and could be left as a nurse until about ten years of age. However, it should be kept in mind that the selection ratio of crop trees is reduced by half if half of the trees are Douglas fir to be culled. Unimproved seedlings available for alternative species require high selection ratios, so generally these should be planted at high stocking rates to produce a well selected crop of good trees.

Alder may prove to be a particularly good nurse in eroded steeplands because it grows well in slip faces devoid of topsoil, fixes atmospheric nitrogen into the soil and provides leaf litter to rebuild topsoil. It also is vigorous as a young tree but "runs out of steam" allowing the crop trees to take over after being forced upward, thus minimising branch index.

Manuka has been suggested as a suitable nurse crop on erodible steeplands that also yields valuable honey and thus a short term income stream while the timber crop establishes. Manuka is naturally succeeded by climax species so such a regime would mimic natural reversion, rather than planting manuka as the primary crop and then having to maintain the species dominance through management.

Quality characteristics by species

Estimating the suitability for plantation species to control erosion on steeper slopes has not yet been refined and quantified. Subjective species ratings and quality ratings are presented here using professional judgement, with the goal of refining these as research improves our understanding of the importance of each quality and how the species perform comparatively. This method could be seen as a first attempt to develop a method for evaluating the suitability of different species for controlling erosion on ESC red zoned land identified in the NES-PF, on a long term basis.

The qualities or species characteristics that vary between species and that influence decisions on species choice are listed below.

The importance of species characteristics is presented here as preliminary ratings for each quality. Some qualities hold higher importance values than others and these importance values could be refined via evaluation studies.

Quality attributes or features

Quality	Importance Rating	Comment
Early growth rate	0.2	Early growth rate is very important in terms of the window of vulnerability. However, increased stocking rate can substitute for early growth rate so the importance of this may be negated. Radiata pine is given an early growth rate of 10 and other species comparative early growth rates are estimated.
Permanent canopy	0.2	The suitability for the species to be grown under continuous cover regimes is important for erosion control on steeper, more erodible slopes. This is only important where clearfell harvesting is not viable or where the level of landslide mitigation requires improvement.
Root decay	0.2	Root decay rate is important because it has an influence on the duration of the window of vulnerability. Species that coppice have slow root decay rates and it is assumed that for species that don't

Quality	Importance Rating	Comment
		coppice, root decay is related to wood durability. That is, the durability performance of the timber is a useful proxy for root durability and thus is a measure of the time after clearfell that root reinforcement of the soil is lost.
Productivity	0.2	Productivity on erodible hill country. Productivity is based on annualised productivity rather than rotation length and therefore ignores the time value of money.
Timber value	0.1	An estimate of the timber value based on species appearance and physical properties. Timber value is assumed to be less important than other qualities, but still an important consideration when selecting a plantation forestry species for erosion control.
Coppicing	0.1	The ability to coppice from stumps that stay alive after harvesting. Coppicing is an important species attribute in terms of erosion control.
Total rating value	**1**	**The importance of each quality characteristic, added together equal 1**

Each species is rated out of ten for each quality. The total rating for the species is then calculated by multiplying the species rating for each quality by the quality importance rating for that quality, then adding these quality results together for the species:

	Alder	Beech, Southern	Blackwood	Cedar, Japanese	Cypress	Douglas-fir	Eucalyptus
Early growth rate	8	1	7	5	9	5	8
Permanent canopy	7	8	8	10	8	6	10
Root decay rate	5	7	7	7	8	5	8
Productivity	4	2	3	8	7	8	9
Timber value	5	9	9	6	8	6	8
Coppicing	8	0	8	0	0	0	9
Total rating for species	**6.1**	**4.5**	**6.7**	**6.6**	**7.2**	**5.4**	**8.7**

	Fir, silver	Kauri	Larch	Pine, radiata	Poplar	Redwood, coast	Sequoia, giant	Totara
Early growth rate	4	1	6	10	9	6	4	4
Permanent canopy	10	8	6	3	8	10	9	9
Root decay rate	4	9	5	2	8	9	7	8
Productivity	8	2	6	10	9	8	7	5
Timber value	5	9	7	3	3	6	6	8
Coppicing	0	0	0	0	10	10	2	0
Total rating for species	**5.7**	**4.3**	**5.3**	**5.75**	**8.1**	**8.2**	**6.2**	**6.0**

The higher the overall rating for the species, the better it should be suited for production plantation forestry on erodible hill country. These ratings are subjective only, but serve to demonstrate that this method could be developed into a more objective tool. Rotation length was not taken into account because this is of less importance than annualised productivity in terms of species selection for erodible steepland country.
Early growth rate is an estimate for each species growth rate compared with radiata pine. A species with a score of 5 equates to half the growth rate of radiata which is 10, therefore twice the stocking is required to achieve the same level of root reinforcement over the same length of time. If the steeplands being harvested and reforested were in radiata pine and a replant stocking rate is determined for radiata that adequately mitigates erosion, stocking rate for an alternative species, to be equivalent in terms of erosion mitigation, would be represented by the equation: `radiata early growth rate/alternative species early growth rate * radiata stocking rate`.
Root decay rate and **early growth rate** together could determine the required stocking rate required to close the window of vulnerability quickest following harvesting and subsequent planting of the cutover.

Models of canopy closure and root occupancy have been developed for radiata pine at different planting densities (Marden et al. 2016). These could potentially be developed for other species to provide the same level of mitigation to that provided by radiata pine at a range of stocking rates. Other factors that might need to be taken into account include rotation length and coppicing ability because these also influence overall risk, along with harvest practice which might include continuous cover, which negates the risk of erosion following harvest.

Root grafting

Information on root grafting of individual species is mostly unavailable, but it can be assumed that trees of the same species will root graft and therefore this quality is equivalent between species. Natural root grafting is common between conifers of the same species (Cerezke, as cited in Harry and Smith, 1964) and grafts between roots of individuals of the same species is common in both conifers and hardwoods (Thomas, 2000). The frequency that root grafting occurs tends to be related to spacing between trees and is less prevalent as trees become further apart (Thomas, 2000).

Why alternative species to radiata pine?

Radiata pine is well known to be an adaptable species that can be successfully grown throughout most of New Zealand (Van Kraayenoord and Hathaway, 1986). In stark contrast, Van Kraayenoord and Hathaway (1986) contended that all other species "have much more specific site requirements", "are prone to various pests and diseases" and "are relatively untested for timber production". These issues suggest a higher level of risk with growing any alternative species to radiata pine.

Eyles (2014), on the other hand, held concerns that "the current emphasis on mass-producing a low-value timber as a monoculture will need to change", in reference to both the biological risk the plantation forest industry faces by depending on one species, and also in recognising the potential for producing higher value timber from other species. Among growers who recognise such opportunities there is a sense of frustration that research into management of alternative species over the last quarter of a century has been discontinuous, ad-hoc and insufficient, resulting in large information gaps that stifle any opportunity for profitably growing alternatives under longer-term rotations in steep unstable hill country (Eyles, 2014). It is well understood that forestry research needs to have a long-term focus and Eyles (2014) pointed the finger squarely at central government for abandoning any national co-ordination of rural sustainability during the 1990's, with the consequence being a lack of research effort into siting of alternative species. The current knowledge pool now resides mostly among farm foresters who have experimented with species and sites (Moore, 2017). This may well be considered insufficient by any serious investor considering planting large areas of these species. Despite these constraints, Moore (2017) suggested that by including carbon in the land-use equation, steep and remote land could be planted in species that produce high quality timber even if rotations were considerably extended.

Radiata forestry on steep slopes is usually considered marginal because of high harvesting costs and commodity log prices. In order to improve returns, either higher log volumes or higher log prices are required. High-value timber species offer the prospect of higher log prices that may produce annualised revenues that exceed those for radiata despite lower volumes, but the current reality is that lack of recognition of specialty timber quality and lack of consistent volumes in the market has resulted in:

- a poorly functioning value chain;
- underdeveloped markets for specialty timber; and
- low log prices despite high retail prices for the timber (Gordon, 2014a).

Adding value to New Zealand-grown specialty timbers in order to generate demand for logs and interest in growing them may require some industry commitment in terms of product promotion, to overcome the "chicken and egg scenario" and drive interest in the species. Of course this conundrum might be viewed by some as a niche marketing opportunity. Moore (2017) suggested that "trees will grow and produce value in the future, irrespective of today’s market. Markets change, and a high quality species on a remote site has more potential than a low quality species".

Extreme environmental conditions such as high winds, poor soil structure, low available nutrients and low soil moisture content can all be present on steepland sites and for trees to thrive they must be adaptable and easy to establish (Van Kraayenoord and Hathaway, 1986).

Knowledge, of course, does continue to improve from anecdotes and experienced enthusiasts in the farm forestry community are willing to share what they have learned after "giving it a go" with alternative species. Formalising such evaluations into research trials that validate the hypotheses may or may not be necessary as knowledge evolves, but because of the inevitably long time frames involved in plantation forestry, knowledge tends to evolve slowly.

Genetics

Genetic gain as recoverable volume per hectare has risen by around 30% in 50 years for radiata pine (Moore, 2017) as a result of a comprehensive and well-funded breeding programme. Meanwhile, alternative species to radiata pine and Douglas fir have suffered from an "almost complete lack of any selection for improved performance" (Gordon, 2014a). One method for overcoming lack of genetic improvement is to plant at a high stocking to provide a high selection ratio for growth and form. High tree stockings can also reduce branch index, but thinning in multiple progressive operations would be required to minimise windthrow in crop trees while ensuring adequate diameter increments. High initial tree stockings also reduce erosion risk in steeplands, so regimes could be deployed with unimproved seedlings that are nevertheless productive, but do require a higher initial capital outlay than genetically improved radiata.

Risk

Assessing risk is about identifying and evaluating those risks, which include wind, fire, snow, insect damage and diseases (Moore, J. 2014). That risk varies between species and sites and radiata pine is by no means immune to these; for example red needle cast outbreaks and periodic snow damage in some localities. In terms of biological risk, Van Kraayenoord and Hathaway (1986) questioned the advisability of planting monocultures and perhaps the opportunity steepland forestry offers to the sector is how to do things better.

Strong wind can break tops out of radiata pine and detrimentally affect both growth rates and form (Moore, J. 2014). Log grades can be lower from windy sites both because of malformation and also larger branches (Moore, J. 2014). Radiata grown in windy sites can also produce wood with less stiffness and more resin pockets compared with trees grown in more sheltered sites (Moore, J. 2014). Perhaps species better suited to windy sites could produce better returns than radiata in exposed steeplands. Unfortunately, evidence of the relative wind-firmness of alternative species to radiata pine is mostly anecdotal (Moore, J. 2014), albeit with some species clearly demonstrating high resistance to wind and others less so.

Management decisions also influence risk of wind damage to plantations. Thinning increases the risk for the residual stand to suffer from wind damage, especially where thinning is late and trees are tall and thin (Moore, J. 2014). Harvesting also increases the vulnerability of residual trees to wind damage that were left after harvesting trees adjacent to them (Moore, J. 2014). Increased rotation length also may increase the risk of storm damage (Moore, J. 2014). On steepland slopes, high initial stockings of trees may be required to shorten the window of vulnerability, especially with slower-growing species. These plantings may require multiple progressive thinning operations to reduce the risk of windthrow and produce sufficient crop tree diameters. Cost effective methods for progressive thinning to waste include ringbark thinning (Satchell, 2018).

Site requirements

Site requirements vary considerably between species. For example, pine species that are more suitable than radiata to colder, drier areas of the South Island include *Pinus nigra* subsp. *Larico*, *P. muricata* (blue strain) and *P. ponderosa* (Van Kraayenoord and Hathaway, 1986). Within species, determining suitability of provenances may be necessary to ensure climatic compatibility (Van Kraayenoord and Hathaway, 1986). Where a site has extreme variability in terms of soil structure, moisture, temperature and light intensity, an adaptable plant species is required, or alternatively a good understanding is required of the species adaptability to site (Van Kraayenoord and Hathaway, 1986).

Species with weed potential should be avoided for soil conservation plantings (Van Kraayenoord and Hathaway, 1986), which precludes planting of Douglas fir, larch and some pine species where these have potential to spread as wildings. Site also influences a species weed potential, which includes neighbouring land's vulnerability (Ledgard, 1999). Decision support systems are provided by MPI under the NES-PF, including the Wilding Tree Risk Calculator, which rates the spread risk using the following indicators:

- Tree species type (spreading vigour)
- Palatability of tree species to stock
- Site location
- Site characteristics
- Existing vegetation on site

See the MPI Wilding Tree Risk Calculator.

Root habit may be important for preventing erosion. Species that are desirable for erosion control have a root system that develops rapidly, is extensive and binds soil together to resist tensile stresses (Van Kraayenoord and Hathaway, 1986).

Establishment of trees on seasonally dry sites can be difficult. This may require complete elimination of weeds and grass competition from around the tree during its establishment by using herbicides (Van Kraayenoord and Hathaway, 1986).

Colonising plants are the most suitable for rapid revegetation of eroded soils where topsoil is depleted, especially species that produce new plants from suckers or root fragments, or plants that fix atmospheric nitrogen to enrich the soil ecosystem (Van Kraayenoord and Hathaway, 1986). Tolerance of stem burial and development of adventitious root systems and other means of regeneration after disturbance offer improved erosion-proofing (Van Kraayenoord and Hathaway, 1986).

Native timber trees generally have slower growth rates compared with exotic species, so reinforcement of soils would be delayed (Jones et al. 2008).

Timber production

Commercial plantation forestry investment demands a species that maximises production of logs that are of a quality and value that provide adequate returns to the investor. However, a survey of small forest owners found that primary drivers for forest investment also include best land use (West and Satchell, 2017), suggesting that some owners may be willing to trade off returns for environmental outcomes. Where erosion control is the primary objective, species selection criteria may be different from production-based plantation forestry.

Converting logs into value-added products that command high prices in the market and in sufficient volumes that fulfil market expectations may be a prerequisite to generating interest in planting high-value species in New Zealand (Gordon, 2014a; Satchell, 2015). Moore (2017) emphasised that the lack of a current market for locally grown specialty wood is only an education problem and that markets do change (Moore, 2017), so should deployment precede market development?

For some species market demand for logs has increased dramatically in the last few years as the export log market has matured and log exporters buy most available species, often at a premium (A. Laurie, pers. comm). Trost (2005) found the local market for logs to be much more sensitive to log quality and limited in capacity, with a preference for logs that produce lengths of timber that are clear or timber with tight knots for discerning appearance applications. This may be changing as local specialty mills compete with the export market for logs and market demand for knotty appearance timber grows (J. Fairweather, pers. comm). Although "the market for special purpose timbers is relatively small, and there is only a limited number of sawmillers who are experienced in handling these species" (Trost, 2005), this may well change within a rotation length.

Other impediments constrain market demand for high-value timber species in New Zealand. Our performance-based building code has a history of compliance paths offered for radiata pine and Douglas fir, but not for other species, despite their superior properties. By not being code-complaint, a range of products and applications for specialty timbers are effectively removed from the market, negatively impacting on demand for timber and prices for logs (Satchell et al. 2016). Developing markets for high-value specialty timbers could of course be viewed as a hurdle rather than a brick wall, with current industry efforts attempting to address this with the Specialty Wood Products programme led by the forest industry in partnership with MBIE.

Alder

Alder species are used for erosion control in many countries, especially infertile sites (Naghdhi et al. 2013; Stokes et al. 2009 as cited in Phillips et al. 2015b).

Red alder (*Alnus rubra*) is easy to establish, is nitrogen fixing and relatively fast growing, reaching 40 cm diameter in 25 years on riparian margins (May, 2017).

Management

Red alder, open ground sown and bare-rooted, was tested for early root growth and was found to be the best performing species in terms of height, lateral root spread and total root length and was therefore considered to be "a prime candidate for consideration as an erosion control species" (Phillips et al. 2015b). However, this trial was located in a sandy loam alluvial terrace near Gisborne with a seasonal water table (Phillips et al. 2015b), which may have suited the species compared with eroded and erodible hill country. However, alders have been used overseas to consolidate landslips (Phillips et al. 2015b)

Italian alder (*Alnus cordata*) has been successfully used as a nitrogen-fixing nurse crop for redwood in Manawatu hill country, interplanted as every second tree. The alder had faster initial growth and forced the redwood upward and with small branches. The redwood from about ten years of age began to dominate the alder and by year 13 was overtopping it, with all redwood branches remaining alive and small (P. Silcock, pers. comm).
Caucasian alder (*Alnus subcordata*) is one of the larger growing alders in New Zealand (T. Rose, pers. comm).

Alders can grow well in poor soils, provided these do not dry out and have been observed to grow twice as fast on southern-facing slip faces than on quality adjacent soils. (B. McNeil, pers. comm).

Timber

Red alder timber is easy to mill and season and "produces a stable, medium density, light brown timber suitable for panelling, joinery and furniture" (May, 2017).

Red alder is easily worked, glues well, takes a good finish and is increasingly being used for furniture and cabinetry. (Walton, 2009).

Clearwood red alder retails in North America for over $2,000 per cubic metre (May, 2017).

Beech, Southern

A number of Southern beech species are indigenous to New Zealand. These are all evergreen broadleaved hardwoods and include silver beech, red beech, hard beech, black beech and mountain beech. Leaf shape is the major characteristic used for distinguishing these species.

Beech is widespread throughout cooler areas of New Zealand and constitutes over half of the remaining native timber resource in the country (Smale et al. 2012). The New Zealand beeches "produce high quality functional and decorative timbers" and "substantial areas of manageable beech forests remain in freehold and Maori tenure" (Smale et al. 2012). The red and silver beech resource is estimated as being able to sustainably produce 200,000 m^3 of sawlogs per annum (Smale et al. 2012). Historical constraints to developing this resource included low native softwood timber prices, cheap imported timber and opposition to harvesting native trees (Orwin as cited in Smale et al. 2012). Log volumes harvested in 2011 were just over 10,000 m^3 (Ministry of Agriculture and Forestry as cited in Smale et al. 2012).

Management and silviculture

The beeches are amongst the fastest-growing of all planted native trees and "present good prospects for plantations" (Pardy et al., as cited in Smale et al. 2012). Beech can be managed by either continuous cover with selection, or a uniform system (Barton, 2005). However, there is evidence that clearfelling, even where undertaken in coupes, is not effective unless the coupes are small and retain side shelter (J. Wardle, pers. comm). Once released into the open, trees are subject to sun-scald in the bark which brings in rot and dessication of the crown (J. Wardle, pers. comm). Beech are considerably more difficult native species to manage in plantations compared with succession species like totara and rewarewa (J. Wardle, pers. comm). Selective harvesting while retaining a canopy offers the most reliable option for managing beech plantations (J. Wardle, pers. comm).

Form is generally similar for the beech species, with open growing trees having short trunks, horizontal branches and spreading crowns, whereas trees in denser stands have longer trunks, more upright branches and shallower crowns (Smale et al. 2012).

Beech tends to have a shallow root system but root grafting occurs in all species and may improve tree and slope stability (Smale et al. 2012).

Seeds are relatively heavy with small wings, so are not bird-dispersed and fall within the vicinity of parent trees, limiting the advance of existing stands (Smale et al. 2012). Although beech seedlings regenerate prolifically in existing forests, they are very vulnerable to drought in the first year of establishment (Smale et al. 2012). Mycorrhizal associations offer improved growth rates for beech seedlings and are considered to be an important association for establishment of beech (Smale et al. 2012).

Seedlings are easily raised in nurseries either as containerised or bare-rooted two-year-old stock (Smale et al. 2012).

Poor survival of planted stock is usually attributed to smothering by grass, rabbit and hare damage and drought during the first summer, especially where seedlings were planted into mineral soils (Smale et al. 2012). In cold climates there is also a risk of unseasonal frosts and winter desiccation damaging or killing seedlings. Desiccation is caused by very cold soil preventing roots from absorbing moisture, combined with desiccating winds that dry the plants (Smale et al. 2012). Neither desiccation nor frosting tends to affect larger saplings or trees, even where open-grown (Smale et al. 2012).

Drought can weaken or kill beech trees, predisposing them to attack by pathogens (Hosking & Hutcheson; Hosking & Kershaw, as cited in Smale et al. 2012).

Open-grown beech has improved survival prospects if a fast-growing nurse species such as manuka is first established (Smale et al. 2012). Manuka appears to have a shared mycorrhizal association with beech and beech may benefit from such an association beyond amelioration of above and below ground microclimate (Smale et al. 2012). By using a nurse species, side shading shelters crop trees on exposed sites, improves early height growth, reduces branching and decreases incidence of multiple leaders (Smale et al. 2012). Manuka has good potential as a nurse crop for beech because although it may overtop beech in the early establishment years, beech emerges through the manuka and outcompetes the manuka (J Wardle, pers. comm).

Regular releasing from competing vegetation is necessary for up to five years after planting of beech seedlings and the addition of fertiliser is necessary on grossly infertile sites (Smale et al. 2012).

Planting beech at high stockings such as 2 m x 2 m offers relatively early canopy closure and associated improved form and smaller branch size, but reduced diameter growth. Lower planting stockings require more form pruning to ensure single straight stems and more pruning to ensure branch-free stems (Smale et al. 2012). In general terms, unless the grower is willing to put in considerable effort into form pruning, low initial stockings are not likely to succeed and open growing of trees should be avoided (J. Wardle, pers. comm).

New Zealand beech species don't tend to coppice, although this can occasionally occur with silver beech (J. Wardle, pers. comm).

In beech forests natural regeneration is at very high densities, which produces good form and branch control, but at the expense of fast growth. Up to 100 years is required for dense stands to self-thin. Silvicultural intervention has the potential to greatly increase yields of merchantable sawn timber and shorten rotation lengths, in particular multiple light thinnings (Smale et al. 2012). Height growth is maximised where stems are sheltered by adjacent trees but are far enough away from them to reduce competition (Smale et al. 2012). Diameter increments in plantations can be between 8 mm and 9 mm per annum, with similar growth rates between species, but best growth is attained in fairly open stands in mild climates and with fertile soils (Smale et al. 2012).

With their stronger apical dominance, red beech and black beech can be thinned earlier and heavier than silver beech (Smale et al. 2012). Silvicultural systems aimed at producing high-quality timber can achieve 45 cm DBH sawlogs on rotations of 50-55 years, provided stands are slowly but progressively thinned down to 450 stems per hectare, beginning from twelve years of age, with pruning of all crop trees practiced (Wardle, 2005). Current recommendations for mixed-age stands are for 600-800 stems per hectare and 500 stems per hectare for even-aged stands (J. Wardle, pers. comm). Average harvest age for well managed black beech is 60 years with a range of 40-80 years (J. Wardle, pers. comm). With mixed age selective systems there is significant economic advantage in terms of harvesting each tree to maximise returns, which means that where growth rates vary according to topographic variation, the time taken to reach optimum economic value will vary accordingly (J. Wardle, pers. comm).

Without careful form pruning, beech planted at wide spacing will have poor form, short boles and large branches (Smale et al. 2012). Even at stem densities of 2 m x 2 m, beech will require form pruning of multiple leaders and branch pruning to ensure a branch-free single lower trunk develops (Smale et al. 2012). Pruning can result in production of epicormic shoots in open stands of planted beech (Smale et al. 2012).

Siting

Beech should only be planted in suitable climates. For example mortality of red beech seedlings can be high in warmer lowland regions, with better survival in cooler climates (Smale et al. 2012). Where possible local provenances should be used to ensure trees are well adapted to site (Wilcox & Ledgard, as cited in Smale et al. 2012).

Provenance trials of beech species showed that:

- red beech is fairly uniform as a species but silver beech is genetically variable;
- black beech is faster growing than mountain beech and on a par with red beech; and
- a third form of this species from well-drained lowland sites in the South Island, with seedlings intermediate between mountain beech and black beech, was found to be among the fastest growing of all the New Zealand beeches (Wilcox & Ledgard, as cited in Smale et al. 2012).

This third form offers reasonably fast growth rates and reasonably high density timber that is faster to dry than red beech (J. Wardle, pers. comm). Indeed black beech could be a stable hybrid between red beech and mountain beech (J. Wardle, pers. comm). Black beech may be the best option for exposed eroding hill country in the North Island because it tolerates poorer soils, is a lowland species, is a moderate competitor and is present in the lower North Island on exposed ridges with hard dry soils (J. Wardle, pers. comm).

Silver beech

Silver beech is a cold hardy species tolerant of heavy frost and snowfall (Smale et al. 2012). Silver beech is the most tolerant species of shade, so trees can grow up beneath existing canopy trees (Smale et al. 2012). Silver beech has weaker apical dominance than the other beech species and requires side shade for good form (Smale et al. 2012). Silver beech is also slower growing than the other beech species, prefers higher rainfalls and is less tolerant of infertile or poorly drained soils than mountain beech (Smale et al. 2012).

Black beech and Mountain beech

These species tolerate cold and dry conditions better than the other indigenous beech species. Rainfall can be as low as 750 mm per year for black beech, which is a lowland species that can achieve good growth rates (Smale et al. 2012). Mountain beech grows at higher altitudes in fairly dry conditions and is the least tolerant of shade, but is very tolerant of frost (Smale et al. 2012).

Black beech is usually found in conditions between mountain and red beech (J. Wardle, pers. comm).

Red beech

Red beech, along with black beech, are the fastest growing of the beech species and red beech attains the largest size (Smale et al. 2012).

Red beech is intermediate in terms of shade tolerance and is less tolerant of frost than silver beech and Mountain beech (Smale et al. 2012).

Red beech prefers lower altitude fertile sites (J. Wardle, pers. comm).

Hard beech

Hard beech is a lowland species more suited to warmer climates than the other beech species (Smale et al. 2012). Hard beech is intermediate in terms of shade tolerance, tolerates poorer and drier soils than red beech, but is less tolerant of frost (Smale et al. 2012). Hard beech grows on hard infertile soils and being very resistant to wind exposure, is often found on bony ridgetops (J. Wardle, pers. comm).

Hard beech produces an attractive and hard timber, but is difficult to saw (rapid blunting of blades) and dry (case hardening) (J. Wardle, pers. comm).

Pests and diseases

Beech species are not a preferred food source for either possums nor deer (Smale et al. 2012).

All five beech species are attacked by pinhole borer (Platypus spp.). Although sawn wood and logs can be attacked, as soon as the surface of the wood dries it becomes less attractive (Smale et al. 2012). Trees that are damaged or under stress from drought or competition are more likely to be attacked and fast growing trees may be more susceptible. Older trees may be less vulnerable to attack (Smale et al. 2012). Management of pinhole borer is by reducing quantity of brood-rearing wood (Smale et al. 2012).

Pinhole borer is less likely to be a problem in managed plantations compared with natural stands because the point of infestations such as collapsing older trees is not likely to be present and therefore the innoculum potential would remain low (J. Wardle, pers. comm).

Platypus is also a vector for the *Sporothrix* fungus, a pathogen that discolours wood or kills wood tissue leading to a core of dead pathological heartwood, potentially killig trees and prompting a new outbreak of pinhole borer (Smale et al. 2012). Saplings "can be attacked by by larvae of puriri moth (*Aenetus virescens*) in the North Island and larvae of the kanuka longhorn beetle (*Ochrocydus huttoni*) in both islands" (Smale et al. 2012).

Many native insects also feed on the canopies of beech and can partially defoliate large areas of Mountain beech (Smale et al. 2012).

Timber

The New Zealand beech species yield medium density hardwood timber with a fine, even texture and straight grain (Smale et al. 2012). Properties are excellent for sawing, machining, turning and nailing (Smale et al. 2012).

Beech wood is suitable for applications where strength, stability and decorative appearance are required. The timber is currently being finished into veneer, furniture, dimensional timber and decking products (Smale et al. 2012). Its fine even texture makes beech an excellent furniture timber and it is suitable for decorative veneers (Smale et al. 2012).

Neither heartwood nor sapwood is subject to attack to *Anobium* borer (Smale et al. 2012). Silver beech sapwood is more susceptible to decay than sapwood of the other beech species (J. Wardle, pers. comm).

Silver beech is easy to dry and black beech is also moderately easy to dry (Smale et al. 2012). The presence of tension wood makes hard beech and red beech more difficult to dry, particularly in larger sections (Smale et al. 2012).

Black beech is strong, stable and durable (Smale et al. 2012). Heartwood of black beech dries to a straw colour and the sapwood whitish-brown (Smale et al. 2012). It is used for furniture, exposed floors and interior joinery and tool handles (Smale et al. 2012).

Red beech heartwood is light red to medium red-brown in colour and the sapwood light brown to white (Smale et al. 2012). Heartwood is strong and durable and the wood has exceptional dimensional stability (Smale et al. 2012). Red beech timber is close grained and has a lustre and sheen that tends to improve with age, along with fine turning properties and achieves a very smooth finish (Smale et al. 2012). Red beech is used for furniture, exposed flooring, stair treads and decorative interior finishing, along with exterior decking and pergolas (Smale et al. 2012).

Silver beech has a pinkish to red overtone and is an attractive furniture timber with a deep lustre (Smale et al. 2012). Although lighter and more easily worked than the other beech species, it is also less durable (Smale et al. 2012).

Hard beech is light yellow-brown, durable dense and strong (Smale et al. 2012). It is the most difficult of the beech species to saw and season (Smale et al. 2012).

Blackwood

The extensive root system offered by blackwood deserves more attention in stabilising erodible hillsides (Brown, 2006a). Blackwood coppices and suckers freely and fixes nitrogen into the soil, so can be used as a colonising species for permanent erosion control in fairly harsh sites (Van Kraayenoord et al. 1986).

Although blackwood will grow almost anywhere in New Zealand, on dry exposed locations it is slow growing and poorly formed (Brown, 2005a). Blackwood is best suited to lower valley slopes and moist gullies (Brown, 2006a) where fertility is moderate to good and drainage is not severely impeded (Jackson, 2006). If the species is to be managed for timber, blackwood is highly site selective (Brown, 2005a). For fast growth and production of straight logs, blackwood requires reasonable quality soils, sufficient soil moisture and shelter (Brown, 2005a). Eroding gullies, where sheltered and with plenty of soil moisture are suitable sites for productive blackwoods (Brown, 2005a). Gullies with difficult access may suit planting in blackwood because the value of the resulting timber would justify extraction (Brown, 2006a).

Establishment, siting and management

Blackwood "has little apical dominance and will form a large branched crown at the first opportunity on as short a stem as possible" (Jackson, 2006). Therefore, form pruning and thinning are essential for sawlog production (Brown, 2005a, 2006a; Jackson, 2006) and "unlike radiata or cypress there is no fallback option of leaving blackwood unpruned." (Jackson, 2006).

The specific siting and silvicultural requirements for blackwood, along with the limited information available on costs and returns currently deters commercial growers from planting the species (Brown, 2006a).

Form pruning must be undertaken annually until at least year eight (Brown, 2006a). The best growth response is produced when blackwood is pruned in spring rather than winter (Brown, 2008).

Thinning must be undertaken in a timely manner, preferably down to 200 stems per hectare to achieve valuable large diameter logs (Brown, 2006a). Ringbarking is effective but is best done in spring when the bark strips easily (Brown, 2008).

Blackwood, being a pioneer species, is intolerant of shade (Brown, 2006b). Jackson (2006) found that good side shade improved form, by row-planting with good site preparation in the rows, but retaining scrub between the rows. Brown (2006b) found that although mixed planting offers benefits of rapid height growth and good form, the response needs to be carefully managed by removing the nurse crop on time (Brown, 2006b). Brown (2006b) suggested form pruning is preferable to the complicated management of nurse crops. Millen (2017) favoured continuous cover management with a gradual removal of trees when they reach millable size, which offers side shade for regeneration, which is prolific and can be managed rather than replanting with new stock.

Coppice grows best in Autumn and can be managed for timber production because it tends to grow straight and with good branch suppression (Brown, 2008). Brown (2008) also suggested that thinning of coppice growth can be delayed until the coppice shoots are over eight metres tall, producing acceptable trees with little effort from regrowth.

Average rotation length is 35 years (Brown, 2006a). Bigger, older trees tend to produce the best wood (Esson, 2006).

Insect pests of blackwood in New Zealand are regarded as significant and can affect both growth rates and form (Brown, 2006a).

Blackwoods do not tolerate heavy frosts (Brown, 2005) and incur limb breakages from snow (J. Fairweather, pers. comm; A. Gordon pers. comm).

Weed potential

The weed potential of blackwood is relatively low, although soil disturbance allows regeneration from seed or suckers where there is sufficient light (Brown, 2006a). Thus sucker growth can be prolific on a harvested site. Once established, blackwood is difficult to remove from a site, potentially an advantage for erosion control and continuous cover management. Selective herbicides are available that kill it to the roots.

Timber

The special requirements for milling and drying blackwood require experience and understanding (Brown, 2006a) but sawmilling is fairly straight forward provided blades are sharp (Li Legler, pers. comm).

Blackwood timber is air dried before finishing in a low temperature kiln (Esson, 2006).

The demand for blackwood timber tends to exceed the supply and prices can be very high (Brown, 2006a; Esson, 2006). However, only niche quantities are being produced currently in New Zealand and a sudden increase in supply could potentially destabilise market value. Export markets tend to depend on consistent quantities, which may be possible as supplies increase.

The market prefers lengths that are as long and as clear as possible and heartwood only (Esson, 2006).

Cedar, Japanese

Japanese cedar (*Cryptomeria japonica*) has a fairly narrow conical habit and can become a very large tree at over 45 m in height and 145 cm diameter in New Zealand (Knowles & Miller, 1997). Despite slower early growth than radiata pine, Japanese cedar is one of the largest volume producers of any plantation softwood species and in one 19 year old plantation near Gisborne achieved an annual increment of 39.4 m^3/ha, with an average diameter of 38 cm at a stocking of 940 stems per hectare (Knowles & Miller, 1997). Best growth is achieved in warmer, wetter areas of the country such as the central and northern regions of the North Island (Knowles & Miller, 1997). Japanese cedar can tolerate damper soils than many other conifer species (Sampson, 2008).

Japanese cedar is an attractive tree and has been widely planted throughout the North Island and Northern South Island, sometimes in plantations (Knowles & Miller, 1997).

Siting

In its natural range Japanese cedar grows at altitudes of between 300 m and 1000 m in areas of fairly high rainfall (Knowles & Miller, 1997). In New Zealand at least 1000 mm of rainfall is required for best growth and although reasonably tolerant of frosts, late frosts can be damaging (Knowles & Miller, 1997). Although altitudes can exceed 600 m, best growth is below this (Knowles & Miller, 1997)

Japanese cedar is a windfirm species and can withstand severe windstorms without windthrow or breakage, although it may not withstand extremely exposed coastal situations (Knowles & Miller, 1997; Sampson, 2008). Japanese cedar is also moderately resistant to snow damage (Cairns, 2012).

Management and silviculture

Silvicultural management should aim to minimise incidence of bark-encased knots. The species has small branches that self-prune to some extent, and the species is relatively shade tolerant. However, where trees become shaded height and diameter growth is restricted (Knowles & Miller, 1997).

Cutting-grown clones have been selected for good form and vigour (Sampson, 2008).

The suggested optimum regime is for an initial stocking of 1670 stems per hectare (2 m x 3 m), pruned to 6 m in three lifts aiming for a diameter over stubs (DOS) of no more than 16 cm, then thinned at 15 years to 800 stems per hectare, then again at 20-30 years down to 400 stems per hectare for a rotation length of 40-60 years (Knowles & Miller, 1997).

Japanese cedar is easy to establish either as seedlings or rooted cuttings and can be planted out either as well-conditioned bare-rooted stock, or as containerised stock (Knowles & Miller, 1997).

Pests and diseases

Japanese cedar is generally healthy in New Zealand and pests/pathogens are only of minor consequence (Knowles & Miller, 1997). Sampson (2008) found that "it has no diseases or pests of consequence and soil pathogens do not bother it at all". However, Japanese cedar is palatable to possums and deer or goats can nip off the leading shoot resulting in multiple leader growth (Knowles & Miller, 1997).

Weed potential

Regeneration has been recorded in the vicinity of planted trees but there are no reports of wilding spread (Knowles & Miller, 1997).

Timber

Wood of Japanese cedar is soft, low density, stable, coarse-grained and fragrant (Knowles & Miller, 1997). Japanese cedar has a relatively high proportion of moderately durable heartwood, which is red-brown in colour, sometimes with streaks of yellow or dark-brown.

The wood of Japanese cedar is not strong and not hard wearing, but being a decorative timber with good woodworking properties it is suitable for appearance applications. These include decorative panelling, joinery, furniture and ornamental posts and poles (Knowles & Miller, 1997). Japanese cedar heartwood is also suitable for exterior cladding.

In Japan the wood is used for structural applications such as framing and laminated beams. Characteristic strength values have not yet been determined for New Zealand material, nor for fixings. Until these are available Japanese cedar will not comply as a structural timber under the building code (D. Gaunt, pers. comm).

Cypress

Macrocarpa and cypress have been planted for shelter, shade and aesthetic values for well over 100 years throughout New Zealand, primarily because of easy establishment and good growth rates (Satchell, 2017). Because of the highly regarded wood properties and domestic demand for the timber, macrocarpa has emerged as a viable plantation forestry option for growers. However, siting requires care, as does management for high quality timber.

Stand management and siting

Cypress is reasonably site demanding, with a range of environmental factors that regulate productivity, including level of wind exposure, salt laden winds, soil moisture, depth and fertility (Satchell, 2017).

Tantrum (2005; 2010) suggested that good drainage is necessary for a successful cypress crop. High soil moisture combined with high soil fertility together encourage vigorous foliage growth while discouraging root development, thereby inducing toppling (Brown, 2005c). Cypress planted on fertile ex-farm sites subject to periodic high wind and heavy rain events are particularly vulnerable to toppling (Brown 2005c). However, toppling is rare in low fertility, dry, exposed sites (Brown, 2005c), suggesting the combination of fertility and high soil moisture are to be avoided. Wide spacing of trees could also increase the risk of toppling on fertile ex-pastoral sites (Fitzsimons, 2014).

For fast growth rates macrocarpa requires more soil fertility than radiata pine (Hocking, 2006) but significantly less than redwood (D. Tantrum, pers. comm). Tantrum (2010) suggested that both reasonable soil fertility and reasonable rainfall are required for good cypress growth. However, cypress has proven to be very resilient to climatic extremes and although slower growing, can tolerate both low rainfall and low fertility sites (Satchell 2017). Cypress species can be matched to most steepland hill country sites in the North Island and are well suited to the soils of erodible hill country, provided these are not skeletal and there is some fertility (D. Tantrum, pers. comm).

Resilience to wind exposure is highly dependant on clone or species (Satchell, 2017). Macrocarpa has "excellent tolerance to extreme salt wind, even salt spray" (Hocking, 2006b), while Leyland cypress can grow in adverse conditions and tolerates both exposure and also dry sites (Brown, 2005b). Lusitanica cypress, on the other hand, is not tolerant of exposure to wind, especially salt laden winds (Milne, 2006a). Himalayan cypress (*C. torulosa*) is extremely tolerant of dry conditions and wind exposure and although it is slower growing than other cypress species, produces better results on bony exposed ridgetops (D. Tantrum, pers. comm).

Nootka cypress hybrids (e.g. Leylands, Ovensii) are more adaptable to low soil fertility than macrocarpa and lusitanica (Milne, 2006b; Satchell, 2017) and are likely to have greater tolerance to cool and wet conditions (Milne, 2006b). One particular Nootka hybrid clone, Oven's cypress ("Ovensii"), has proven to be healthy, vigorous and adaptable to site and grows well throughout most of the country (Milne, 2006a; Satchell, 2017). Some limitations have been reported, in particular it's intolerance of hot, dry or exposed sites and salt laden winds (Milne, 2006a). Observations suggest that Ovens cypress does grow well on exposed inland North Island sites (S. Rapley, pers. comm), even Wairarapa where strong hot winds are common (N. Cullen, pers. comm), but not in South Otago where winds are very strong but also cold (N. Cullen, pers. comm).

Pruned regimes

Long rotation lengths are required for a cypress clearwood regime in order to produce high volumes of the more valuable clear heartwood, and extended rotations of macrocarpa offer the potential to produce very high returns (Laurie, 2013).

Production of high value pruned buttlogs on 36-40 year rotations involves:

- Early pruning that minimises the defect core; along with
- severe early thinning down to 300-400 stems per hectare (Trost, 2005).

Such intensive management, it is argued, improves economic value by optimising recovery of clear heartwood available for processing (Trost, 2005). However, for highest returns, the pruned buttlog regime would take into account the tradeoff between headlog quality and buttlog volume and although the aim is for large diameter trees that produce large volumes of clear heartwood:

1. Reducing tree stockings to low numbers in order to produce large diameter trees carries with it a risk of windthrow resulting from a reduced basal area (J. Moore, pers. comm).
2. Trees respond to early thinning by producing large branches and knots, which also cause degrade and timber defects in the headlog that severely limits value (Thomsen, 2011).

Thomsen (2011) therefore suggested that competition needs to be retained for long enough to restrict branch size in the headlog. Delayed thinning, in contrast to severe early thinning, produces deeper crowns and less tapered trees (J. Moore, pers. comm). However, radial increment is slowed in order to achieve height growth, finer branching and better quality headlogs. This intervention point, if delayed for too long, would result in excessive height to diameter ratios, which carries with it an increased risk of windthrow, together with a higher risk of bark encased knots forming in the wood from dead branches (J. Moore, pers. comm).

Macrocarpa and cypress have good tolerance to shade (Hocking, 2006b), suggesting that live branches are retained well, even under high stocking levels. Macrocarpa also "tends to produce larger numbers of branches and larger branches than other cypresses which makes for more expensive pruning" (Hocking, 2006). Therefore controlling level of branching with tree stocking would appear to be a sensible strategy to improve unpruned log value and reduce management costs. However, balancing the need to maximise productivity and fully occupy the site with the need to thin down to an appropriate stocking that maximises production of clear heartwood i.e. logs with sufficient diameters, while at the same time mitigating the risk of windthrow, involves a strategy of gradually but progressively removing a proportion of the basal area over time (J. Moore, pers comm.). Thinning severity needs to be carefully managed.

Younger, smaller diameter pruned trees have a high percentage of sapwood and will only yield low volumes of clear heartwood (Satchell, 2013a). However, if the DOS is kept to a minimum, high recoveries of clearwood that includes sapwood is possible in rotations as short as 20 years (Satchell, 2013a). That said, level of market demand for clearwood that includes sapwood has not been resolved. Nevertheless, silvicultural operations that produce a very small DOS considerably improve recovery of clearwood regardless of rotation length, especially the higher value clear heart (Laurie, 2013; Satchell, 2013a). This requires pruning little and often (Tantrum, 2010), which is costly but justified by the value of the crop.

Intensive management and impeccable timing of silvicultural interventions may not be a suitable regime for steeplands. Where intensive management isn't practiced, rotation lengths of 50-60 years may offer best clearfell value recoveries (Trost, 2005), because "Big trees yield a higher percentage of clear timber" (Tantrum, 2010).

Unpruned regime

Although individual trees are generally slower growing than radiata pine, because cypress has to some degree fairly consistent wood properties from pith to bark (Scion, 2014) and its shade tolerance offers high basal areas in short rotations provided stocking is high, young unpruned trees with small diameters can potentially produce good volumes and returns, provided sawn recoveries of appearance grades were achievable from small diameter logs (Satchell, 2017). However, because the durability of inner heartwood tends to be lower than for outer heartwood (Dungey et al. 2014) and the percentage of sapwood is high in smaller diameter logs, the regime is contingent on market demand for sawn product that can include sapwood.

Small diameter sawlogs, because knots are small and green, are still able to be utilised for high value products and "a small unpruned tree yields better timber with green knots than one that has been pruned" (Tantrum, 2010). This is because "small diameter pruned trees produce very little clear timber and what is not clear usually has pruning scars which make it unsuitable for dressing grade" (Tantrum, 2006). Silvicultural management for short rotations would aim only to minimise bark encased knots and maximise volume production of logs above a minimum utilisable diameter. The trade-off is between knot size and log diameter. Dead knots only occur when stands are thinned too late and after branches have died, with a subsequent growth response (such as from thinning). Although unpruned cypress would likely require some thinning to ensure log diameters are sufficient for processing, in a clearfell setting returns as annualised volume production depend on only two factors, rotation length and stocking. The customised regime simply requires either a predetermined rotation length that determines final crop stocking, or a predetermined final crop stocking based on required diameters, that sets rotation length. This takes advantage of the ability for cypress to produce large basal areas in a relatively short time and offers a simple management regime that either culminates in clearfell, or develops into selective harvesting under a permanent canopy.

Thinning of highly stocked stands of trees with dense crowns can be problematic (M. Dean, pers. comm). Ringbarking offers a cost efficient method for thinning cypress (Brown, 2005c; Satchell 2018) and is practiced commercially for cypress that is planted at high stockings to both give high selection ratios and also to control branching (Growing cypresses for timber, Some Example Regimes).

The simplicity of an unpruned regime has appeal for hill country plantations because of the low levels of silvicultural intervention required and the versatility in terms of rotation length (D. Tantrum, pers. comm).

Individual species requirements and management

Macrocarpa often produces heavily fluted buttlogs. Both genetic and environmental influences appear to contribute to fluting (Hocking, 2006).

Cypress canker disease is regarded as the biggest constraint to success with cypress as a plantation species (Satchell, 2017). Tantrum (2010) suggested that cypress canker is caused by stress − "too wet, too dry, too exposed, over pruning, mineral deficiency or any other reason causing stress to the trees". Some attribute the cause of canker to mineral deficiencies in the soil (A. Laurie, pers. comm). Satchell (2017) found that genotypes resistant to canker are available and the focus should be on breeding for resistance.

Macrocarpa performs best in cooler regions because of the risk of canker (Milne, 2006a). Hocking (2006b) claimed that problems with cypress canker may be due to misplacement and mismanagement, with the worst canker normally reserved to exposed north facing slopes. However, after comparing the same clones across a range of sites, Satchell (2017) concluded that canker-tolerant clones are resilient across all sites, offering flexibility in terms of matching clone to site. However, clonal (cutting-grown) trees are slower to establish and are more expensive (Tantrum, 2010). Growers of less resilient seedlines and clones might best follow Hocking's (2006b) advice that although "sometimes things work better than expected on less than ideal sites", macrocarpa is best planted on cool sites such as Southern slopes".

Thomsen (2011) suggested that lusitanica cypress has the best potential for timber production on medium to good quality sites. However, because there is so much genetic variability in the seedling planting stock currently available in New Zealand, planting numbers need to be high for sufficient selection choices (Thomsen, 2011). On moist sites, young trees are vulnerable to toppling, which can be addressed to some degree by tip pruning, i.e. cutting 50% off large branches annually (Thomsen, 2011). However, cypress is vulnerable to toppling at all ages and simply avoiding planting the species on moist sites appears to be the best solution to avoid toppling later on.

Leyland cypress clones have performed well in most areas, but have proven to be susceptible to cypress canker on some North Island sites (Milne, 2006b). Leylands are slower growing than macrocarpa and lusitanica and tend to be more heavily branched, but with straighter stems (Low, 2006).

Cupressus torulosa (Himalayan cypress) has a high quality scented light-brown timber, good narrow pyramidal form, excellent health and tolerates very dry and windy sites, but is slower growing than macrocarpa and lusitanica (Milne 2006a). Thomsen (2011) suggested *C. torulosa* is a good option for medium to poor quality sites because it is tolerant of dry, cold and windy conditions. The timber is highly scented and with a golden colour similar to macrocarpa (Satchell, 2010b). Lawsons cypress *Chamyaecyparis lawsoniana* appears to grow best in cooler sites that are also fertile (Milne, 2006a).

Propagation is by either seed or cuttings and stock is either provided bare-rooted or containerised. Bare rooted cypress survive well if planted in the winter and are usually lower cost than container-grown trees. Seedlings are highly variable in both form and growth and are often planted at high stockings, whereas improved clonal stock offers good form but on average has slower growth rates than seedlings (D. Tantrum, pers. comm). Scion have a breeding programme well underway for cypress that aims to provide growers with improved clonal and seedling stock (H. Dungey, pers. comm).

Cypress are cold hardy (Milne, 2006a) and can be planted in sites too frosty for establishment of radiata pine (M. Self, pers. comm).

Snow damage to young trees can cause severe stem deformation, in particular to lusitanica and macrocarpa, whereas Arizona cypress (*C. arizonica*) and the nootkatensis hybrids (Leylands and Ovensii) can withstand heavy snowfalls (Wardle, 2012). As mature trees, lusitanica suffers from little snow damage whereas macrocarpa can suffer extensive branch breakage and stem deformation (A. Gordon, pers. comm). Lawson cypress and the Nootka cypress hybrids (the Leylands and Ovensii), because of their thin horizontal or downwards pointing branches, shed snow and withstand heavy snow events (Cairns, 2012).

Stock and deer can cause extensive damage by stripping bark from trees (Purey-Cust, 2011). Possums can strip bark from the growing shoot which can result in poorly formed trees (M. Parker, pers. comm) and kaka is an emerging threat.

Milling and Marketing

Very high returns can be expected from well managed and mature stands of macrocarpa, provided there are available markets that are focussed on high-end uses for the timber (Laurie, 2013). Domestic demand for high quality cypress timber is limited however, and log prices could be vulnerable if supply begins to exceed demand (Laurie, 2013). However, if this were to occur, export markets for sawn timber would likely be available to Asia and export markets are currently available for logs (A. Laurie, pers. comm).

Cypress timber is used for higher-value appearance applications such as doors, joinery and kitchens and those requiring stability such as boat building (Low, 2006). Strength is similar to radiata pine, but stiffness is lower (Low, 2006). In particular, younger lusitanica lacks stiffness and strength, but this increases with tree age (Low, 2006).

Pruned cypress logs suitable for producing clear heartwood attain the best market price (Dungey et al. 2014). Heavily branched logs and those with dead limbs have limited market opportunities available (Trost, 2005).

Cypress logs saw well and are very stable, and store indefinitely if only heartwood is required (Tantrum, 2006).

Market preference is for timber that is free of knots or with small tight knots for appearance applications (Trost, 2005), with both heartwood and sapwood suitable for panelling and indoor furniture, and heartwood suitable for outdoor furniture and external cladding. (Dungey et al. 2014). The "magic length for clears is 2.1 metres" (Tantrum, 2006).

Cypress sapwood holds reasonable levels of durability and accelerated decay structural framing tests undertaken by Scion demonstrated durability to be greater than Douglas fir sapwood (Hedley, 2005), which itself is more durable than radiata heartwood (Hedley et al. 2009).

Kiln drying of cypress cannot be practiced from green because the timber cracks and warps (Low, 2006). Air drying is standard practice, followed by low temperature kiln drying (Tantrum, 2006).

Macrocarpa remains the local industry cypress species "timber standard and market preference" (Hocking, 2006b), perhaps because it has a long history of use. Macrocarpa and lusitanica yield a rich honey coloured heartwood, whereas Leyland cypress, Ovensii and Lawsons cypress yield a paler timber. Tantrum (2006) suggested that although darker timber has traditionally been more popular, "some people argue that lighter timber is better because it can always be darkened".

Douglas-fir

Douglas-fir, *Pseudotsuga menziesii*, is native to western North America, growing in humid summer-dry regions with mild climates, from sea level up to elevations of 800 metres in British Columbia (Miller & Knowles, 1994).

Douglas-fir is one of the most valuable and commercially important timber species in western North America (Miller & Knowles, 1994).

In New Zealand Douglas fir ranks as the second most important plantation softwood after radiata pine (Miller & Knowles, 1994) with a total area of approximately 105,000 ha (Ministry for Primary Industries, as cited in Kimberley et al. 2017). Although it eventually becomes a very tall and large-diameter tree, volume growth is relatively slow for the first thirty years (Miller & Knowles, 1994). At higher altitudes where there is a greater risk of wind and snow damage, Douglas-fir performs better than radiata pine in terms of yields, but profitability models for higher quality sites show radiata pine to be the better performer because of the shorter rotation required for the same volumes (Miller & Knowles, 1994) and possibly a log price premium that is marginal. However, exceptional growth rates have been recorded for stands in higher rainfall South Island high country, equivalent to the best radiata mean annual increments (Miller & Knowles, 1994).

Siting

Douglas-fir remains a relatively healthy species in New Zealand, although Swiss needle-cast *Phaeocryptopus gaeumannii*, a disease that arrived in New Zealand in 1959, is considered to be the greatest threat to its health (Miller & Knowles, 1994). Swiss needle cast significantly reduces growth in Douglas-fir, especially where stands are older or unthinned (Miller & Knowles, 1994). Carefully siting the species to favourable sites and avoiding high stocking rates are options for managing the disease (Miller & Knowles, 1994). Damage levels are also lower in coastal provenances so appropriate genetic material should be deployed (Miller & Knowles, 1994).

Douglas-fir prefers moderately high rainfall and moist, free draining un-compacted soils (Miller & Knowles, 1994). On sites where rainfall is less than 1000 mm Douglas-fir prefers shadier, southerly sapects (Miller & Knowles, 1994). Although altitudinal limits are well above 800 m, exposure is the primary limitation to good growth. Douglas-fir is resistant to snow damage (Miller & Knowles, 1994). Douglas fir does not grow well in warmer, more humid northern areas of the North Island (Miller & Knowles, 1994). Thomsen (2011) suggested that Douglas-fir is a good choice for lower altitude Hawkes Bay, provided the site is not stressed for soil moisture and a suitable seedline is selected. Douglas fir prefers a cooler climate, doesn't like hot summers and is subject to disease in the North Island where conditions are warm and humid (M. Dean, pers. comm). The "sweet spot" for Douglas fir may be the Nelson region, where conditions are cool enough for good tree health and warm enough for producing adequate wood density (M. Dean, pers. comm). High wind exposure, such as experienced in many parts of Wairarapa, Canterbury and the southern South Island, is not favoured.

Douglas-fir is considered to be more wind-firm than radiata pine, but "exposure is considered to be the main limitation to its satisfactory growth in New Zealand" (Miller & Knowles, 1994). Strong winds can cause leader loss and crown deformation, but recovery tends to be rapid with little stem deformity resulting (Miller & Knowles, 1994). Stem deformation can also occur on fertile ex-pasture sites (Miller & Knowles, 1994). Exposure damage can be reduced by planting at a high stocking so that establishing trees provide mutual shelter to each other (Miller & Knowles, 1994). Root grafting occurs and improves both tree and soil stability (M. Dean, pers. comm). Where the site has high exposure to winds, radiata shelterbelts are used in New Zealand to both improve form and stiffness for the more valuable Douglas-fir (De La Mare and Hitchings, 2007). *P. radiata* x *P. attenuata* shelterbelts are also showing good potential for sheltering the Douglas fir crop in exposed areas of the lower South Island (M. Dean, pers. comm).

Failure of Douglas-fir plantings can result from late spring or summer frosts at the time when seedlings are flushing (Miller & Knowles, 1994). Well conditioned seedlings with moist roots are required for successful establishment and the planting site needs to be free from weed competition (Miller & Knowles, 1994). Seedlings inoculated with suitable mycorrhizae are required for establishing Douglas-fir on new sites.

Douglas-fir is slower growing than radiata pine for the first few years and very sensitive to weed competition, so releasing is recommended for two to three years after planting (Miller & Knowles, 1994). Tolerance to herbicides is lower than for radiata pine and pre-plant preparation should to be to a very high level (Miller & Knowles, 1994). High survival rates should be aimed for, to ensure even branch suppression because stand gaps result in excessively large branches (Miller & Knowles, 1994). Shaded branches tend to be suppressed quickly and tend to leave sound knots within the stem (Miller & Knowles, 1994). However, Douglas-fir is still subject to black knots and these occur for approximately 8 years after branches become moribund, which is not a problem where these are less than 25mm (M. Dean, pers. comm).

Provenance trials started in 1955 showed that coastal Californian and Oregon provenances were generally more vigorous than those from Washington (Miller & Knowles, 1994). A breeding programme that started in 1970 resulted in a grafted seed orchard being established in 1989, followed by selection of more parent trees from coastal fog-belt provenances in North America (Miller & Knowles, 1994). Improved seed is commercially available but the species requires a continued genetic improvement programme (Miller & Knowles, 1994). Currently, industry routinely plants improved progeny, with seed from first and second generation seed orchards for some provenances (M. Dean, pers. comm). A breeding programme continues to make improvements and is looking to introduce the best families from over 300 tested families of North American imported progeny trialled in NZ conditions (M. Dean, pers. comm).

Silviculture

Douglas-fir is primarily grown for framing timber in New Zealand and is considered to be more dimensionally stable and consistently stiffer than radiata pine throughout much of the South Island (De La Mare and Hitchings, 2007). Douglas-fir is also "highly sought after for use in exposed interior posts and beams because of the species' good stability and low incidence of twist" (Kimberley et al. 2017).

Conservative silvicultural regimes are often practiced with Douglas-fir to ensure production of high stiffness wood, including planting in sheltered locations, thinning lightly and holding high residual stockings (De La Mare and Hitchings, 2007).

Douglas fir will carry a higher basal area per hectare than radiata pine, and although it is considered to be a reasonably shade tolerant species it is difficult to grow under a canopy, so is not suitable for selective harvesting (M. Dean, pers. comm). One conservative method for continuous cover forestry suggested by MacLaren et al. (2006) is to harvest coupe sizes of about 0.25 ha, and harvesting half of the stand when the oldest trees were 60 years old, with half of the stand already 30 years old at that stage.

Tree weeds that are a problem in young Douglas fir stands in the South Island include radiata pine regeneration and sycamore (M. Dean, pers. comm).

Branch size is the most important factor influencing wood quality for structural applications (Miller & Knowles, 1994; Kimberley et al. 2017). A high initial planting stocking of 1600 stems per hectare is recommended in order to limit branch size in the second log (Miller & Knowles, 1994). On dry sheltered sites branching tends to be finer, allowing for a reduction in initial stocking (Miller & Knowles, 1994). Miller & Knowles (1988) also suggested that larch could be interplanted with Douglas-fir as an expendable self-thinning component to reduce the branch size of Douglas-fir. However hybrid larch tends to be more vigorous than Douglas fir for the first 8-10 years so care would be required (M. Dean, pers. comm).

The second most important factor influencing stiffness is wood density (Miller & Knowles, 1988; Whiteside et al. 1976 as cited in Kimberley et al. 2017). Average basic density of sawn timber is generally lower than for radiata pine, reported as averaging 400 kg/m^3 for 50-60 year old trees by Miller & Knowles (1994) and 427 kg/m^3 by Kimberley et al. (2017) for outerwood from 40 year old trees averaged across the country. Density increases gradually with age from about the seventh growth ring from the pith until about thirty years of age, then stabilises (Kimberley et al. 2017). This density increase with age, at approximately 50 kg/m^3, is significantly less than for radiata pine (Miller & Knowles, 1994; Kimberley et al. 2017) at 110 kg/m^3 from rings 1 to 30 (Kimberley et al. 2015 as cited in Kimberley et al. 2017). There is also a density decrease from north to south, approximately 65 kg/m^3 between the central North Island and South Otago (Miller & Knowles, 1994). Kimberley et al. (2017) described this latitudinal effect as a negative relationship between wood density and air temperature, particularly winter air temperature. Cooler, higher elevation sites have lower wood density than warmer sites in the North Island because warmer climatic conditions allow for a longer latewood growth period, meaning the proportion of higher density latewood is greater (Kantavichai et al. 2010b as cited in Kimberley et al. 2017).
Harris (1978, as cited in Kimberley et al. 2017) recommended that average wood density should be above 400 kg/m^3, which is achieved only in the North Island and upper South Island. Improved genetics have led to North Island Douglas fir having a density averaging 462 kg/m^3 for trees planted after 1970 (Kimberley et al. 2017), whereas density for lower South Island Douglas-fir averages approximately 100 kg/m^3 less.

Higher fertility soils also tend to produce lower density wood (Kimberley et al. 2017).

Ring widths in New Zealand grown Douglas-fir are between 3 mm and 6 mm (Miller & Knowles, 1994). Although the effect of ring-width on density is very small, strength does increase slightly with narrowing ring width (Miller & Knowles, 1994). Although increasing ring width can be related to decreasing stand density, stand density has little influence over outer wood density, which is related to number of growth rings (Kimberley et al. 2017). The wood surrounding the pith is lower density than the outer wood. Therefore, as the proportion of basal area comprising this low density juvenile wood increases, then average wood density of the stem decreases. For cooler southern regions where density might be marginal, in order to achieve a satisfactory density without an extended rotation, the percentage of the total basal area comprising juvenile wood might need to be controlled by using a very high initial stocking, especially in more fertile soils, followed by progressive thinning that ensures good growth rates are achieved throughout the rest of the rotation. Longer rotations for larger diameters with a greater proportion of mature wood would still require a silvicultural regime that minimises branch index (larger branches). Breeding trees for greater wood densities offers another option for growers in cooler southern regions to achieve satisfactory wood densities (M. Dean, pers. comm).

For warmer sites, Harris's recommendation (1978, as cited in Kimberley et al. 2017) of growing Douglas fir as rapidly as possible on a short rotation could possibly be followed, even on higher-fertility sites, provided the regime produced a small branch index, because density is not the critical factor determining value.

Strength properties are broadly consistent outside of the central corewood area (juvenile wood), with this being the dominant factor affecting characteristic strength for Douglas-fir (Miller & Knowles, 1994). Miller & Knowles (1994) stated that "wood density and strength do not decrease near the pith, allowing framing timber to be sawn from much smaller logs including thinnings". Indeed, the price differential between log diameters of less than 14 cm and greater than 300 mm is only $15-20 per m^3 for export logs (M. Dean, pers. comm).

Miller & Knowles (1994) recommended to thin to waste before the stand reaches twenty years old, to a stocking of between 300 and 600 stems per hectare, with no further thinning and harvest at about 45 years old. Early thinning ensures diameter growth is maintained and a healthy green crown is encouraged (Miller & Knowles, 1994). Traditional regimes involved rotation lengths of between 60 and 80 years and delayed thinning of trees only once between 30 and 40 years old, which with high land values now results in prohibitive growing costs (Miller & Knowles, 1994).

Current practice is to thin to 500-600 stems at about 15 m mean top height where thinning is to waste (M. Dean, pers. comm). Where terrain and tree form permit production thinning, a waste thinning is undertaken at 10-12 m mean top height to remove poorly formed trees leaving a stocking of 1000-1200 sph, with the first production thinning at 18-20 m mean top height to halve stocking to 500 stems per hectare, then a second production thin at 25-27 m mean top height to 350 stems per hectare (M. Dean, pers. comm).

Weed potential

Because of "its tolerance of wind, snow and low winter temperatures Douglas-fir is often the best species for moister areas of high country" (Miller & Knowles, 1994).
However, Douglas-fir is considered to be a species capable of vigorous wilding spread, in particular "cooler, inland hill and high country areas, where the surrounding vegetation cover and grazing levels can be light" (Ledgard, 2007a). Douglas-fir is also "more shade tolerant than the common pines and will invade shrublands" (Ledgard, 2007). Although Douglas -fir is less palatable to sheep than pine (Miller & Knowles, 1994), well grazed and improved pastures such as found in fertilised, developed farmland pose little threat for spread of wilding Douglas-fir (Ledgard, 2007a). Where there is a risk of wilding spread, despite the site having potential for good Douglas-fir growth, the species should not be planted (Ledgard, 2007a). Species that are less prone to spread such as ponderosa pine and radiata pine are a better choice (Purey-Cust, 2008). Viable seed production occurs from 12 years of age so to removal of wildings before this age short-circuits continued spread (Miller & Knowles, 1994).

The potential for wilding spread in southern North Island hill country should be reduced where there is good rainfall (M. Dean, pers. comm) and in summer-moist areas it doesn't tend to produce cones (C. Low, pers. comm).

Timber

High longitudinal shrinkage near the pith, spiral grain and compression wood, features of radiata pine, are absent in Douglas-fir (Miller & Knowles, 1994). Shrinkage is slightly higher than for radiata pine but Douglas-fir is more stable than radiata pine in response to humidity change (Miller & Knowles, 1994).

Douglas-fir is less suitable than other species for appearance timber, because of difficulties in machining and finishing (Miller & Knowles, 1994). Douglas-fir also requires care in nailing and tends to split at board ends (Miller & Knowles, 1994). Douglas fir can be peeled satisfactorily, however the species has not been used in New Zealand for manufacture of plywood and LVL, possibly because local logs peeled poorly in research trials (Miller & Knowles, 1994).

Douglas-fir can be chipped for manufacture of reconstituted boards and pulp (Miller & Knowles, 1994). It is an important pulpwood species in the Pacific Northwest but its use in New Zealand is limited, possibly because of the high bleach requirement for kraft pulps and poor brightness as mechanical pulp (Miller & Knowles, 1994).

Kiln schedules are recommended to be milder than those used for radiata pine, to avoid surface checking (Miller & Knowles, 1994).

Douglas-fir "will not admit water-borne preservatives " and is regarded as "refractory for preservation because of the difficulty of getting chemicals into the heartwood and dry sapwood" (Miller & Knowles, 1994). For internal structural applications Douglas-fir is listed as suitable for H1.2 boron treatment (NZS 3640:2003).

Eucalyptus

Eucalyptus are hardwood species but with very variable properties between species. Some species have soft, non-durable timber while others yield very hard, very durable timber.

Selecting eucalypt species that grow fast, adapt to a wide range of conditions, are well formed and have good timber properties is considered to be challenging (Gea & Shelbourne, 2006).

Eucalypt species provide nectar and pollen for honeybees and native birdlife (Millen, 2010) and "eucalypts are favoured trees for native birds with tui and bellbirds often looking for insects under loose bark or feeding off nectar from the flowers" (Orchard, 2010). Eucalypts in flower attract insects and insectivorous birds such as fantails (Orchard, 2010).

Durable eucalypt species, because of their ground-durable and extensive root systems that coppice, may be a good choice for combatting erosion (Millen, 2010). Eucalypts are normally coppiced in spring or summer (Brown, 2008). Millen (2010) considered eucalypt species to be well adapted to continuous cover forestry.

Genera

Eucalypts are divided into sub-genera or "families", each with general differences and distinguishing features in terms of siting and wood properties.

Monocalyptus

Monocalyptus species include the stringybark and ash groups of eucalypts. Stringybark and ash group species have proven to grow well in erodible hill country (Gea and Shelbourne, 2006). There is growing evidence that the stringybark group of eucalypts are well adapted to hill country, but site specialisation remains an issue and careful siting is required (Gea & Shelbourne 2006). Stringybarks "handle wind okay" (Satchell, 2006) but on windy hill country have a tendency to fork (Gea & Shelbourne, 2006). Forking of trees can be managed by corrective form pruning (Satchell, 2006) but such intensive management may not be appropriate for steeplands, especially where remotely situated. A high tree stocking is recommended to overcome forking by allowing for selection of straight stems, even from unimproved seedlines (Satchell, 2006). Satchell (2006) also suggested that forking could be easily overcome by breeding of improved stock, in agreement with Gea & Shelbourne's (2006) view that good potential gains can be made after only one generation of breeding.

Stringybark and ash group eucalypts are both in the Monocalypt subgenus, so share the same ecological attributes and tolerances to environmental factors. These are (Florence, 1996):

1. tolerance of low fertility soils;
2. limited tolerance of prolonged dry periods;
3. sensitivity to antagonistic and pathogenic soil organisms.

In their natural environment, Monocalyptus species occupy upper slopes and are replaced by Symphyomyrtus species towards the lower slopes (Florence, 1996). Lower slopes are more likely to have poor soil drainage with a soil water-air balance conducive to root disease (Florence, 1996). In general terms, Monocalyptus species don't like poor soil drainage, with similar requirements to radiata pine (Satchell, 2006). Ash and stringybark eucalypt species have also proven to be highly resistant to pests in New Zealand (Hocking, 2006c; Satchell, 2008; Satchell, 2016) but do require free draining soils (Hocking, 2006c). Ash eucalypts are amongst the more commonly grown eucalypt species in New Zealand but prefer a cooler wetter climate to stringybarks (Hocking, 2010a).

Stringybarks grow at about 90% of the rate of ash eucalypts and depending on species can grow successfully throughout New Zealand (McConnochie & Nicholas, n.d.). Growth rates and site adaptability vary considerably between species, with some species well adapted to cooler areas and others better adapted to warmer conditions (Gordon, 2013). Stringybarks have similar soil requirements to radiata pine and prefer moderate soil fertility with reasonable drainage (Satchell, 2013b).

The stringybark group exhibit high wood density, high strength and stiffness, hardness, and have good natural durability in ground contact (McConnochie & Nicholas, n.d.). Stringybark eucalypts are also well known for ease of sawing and good appearance timber characteristics (Gea & Shelbourne, 2006). Gea and Shelbourne (2006) concluded that stringybark species "show good prospects for sawn timber if form were improved or managed". Current options for managing form include an initial high stocking of trees for high selection ratios, or form pruning (Satchell, 2008).

Ash group eucalypts (*Eucalyptus delegatensis, E. fastigata, E. obliqua* and *E. regnans*) perform well when planted on windy, erodible hill country (Gea & Shelbourne, 2006). Both *Eucalyptus regnans* and *E. fastigata*have been subject to breeding programmes and seed is available with improved form and growth rates (Dungey et al. 2014).

Symphyomyrtus

Symphyomyrtus species are better adapted to heavier, wetter, deeper and more fertile soils of lower slopes (Florence, 1996). However, Gea and Shelbourne (2006) found one Symphyomyrtus species, *Eucalyptus cladocalyx* (sugar gum), to be well adapted to erodible hill country. *E. cladocalyx* is a very drought-resistant species that yields a very durable, high quality timber (Hocking, 2010b). Hocking (2010b) described the form as relatively poor, but improved seedlines from Australian origin are being grown in New Zealand and showing good form (B. McNeil, pers. comm). The Australian work also indicates *E. cladocalyx* has good levels of natural durability and high levels of heartwood (Hocking, 2010b). Other attributes for the species include easy establishment, vigorous early growth, tolerance of very dry, windy conditions and even saline winds, with few insect pests (Hocking, 2010b). The species coppices freely and produces summer nectar for bees (Hocking, 2010b). Negatives include a very thin crown and crown shyness which suggests low volume production per hectare, and the species is somewhat frost tender (Hocking, 2010b). Young *E. cladocalyx* are also very prone to toppling when exposed to a combination of strong winds and high soil moisture resulting from heavy rain (B. McNeil, pers. comm). Hocking (2010b) suggested that *E. cladocalyx* could be a good choice for soil conservation with its extensive, durable root system along with being a species suitable for hot dry north facing slopes. *Eucalyptus cladocalyx* produces high sawn recoveries of high density and high durability heartwood which behaves well during sawing, is light in colour, stable in service and very hard (Hocking, 2010b).

Eucalyptus nitens has proven to be an extremely fast growing and cold-hardy forest species in cooler regions of New Zealand (Satchell, 2015). The species is also very tolerant of wind and can be planted on exposed hill country sites (Gea & Shelbourne, 2006). *E. nitens* is less tolerant of drought than *E. obliqua* (Woodley, 2012) and readily succumbs to an excessively high water table (P. Milne, pers. comm). *Eucalyptus nitens* has been subject to a breeding programme and seed is available with improved form and growth rates (Dungey et al. 2014). The timber has greater strength and stiffness than radiata pine and can produce high quality LVL (Gaunt et al., 2003). However, processing into solid wood appearance products remains problematic because of drying degrade (Satchell, 2015).

Eucalyptus bosistoana and *E. quadrangulata* are two durable species being trialled in dryland areas by the Marlborough Research Company and promoted by Vineyard Timbers. These species have a preference for lowland sites with good soil moisture and are both very susceptible to a range of insect pests (B. McNeil, pers. comm). *E. bosistoana* and *E. quadrangulata* tend to have poor form and require regular form pruning (N. Pollock pers. comm), along with low heartwood content (D. Satchell, unpublished). However a genetic improvement programme is underway.

Corymbia

A third subgenus (now classified as a separate genus) Corymbia, share adaptions and attributes with both Monocalyptus and Symphyomyrtus (Florence, 1996). Corymbia species are well adapted to low soil fertility, can be highly tolerant of dry environments and are also highly resistant to unfavourable soil organisms (Florence, 1996). *Corymbia maculata* (spotted gum), a durable species producing a high quality timber well known in Australia for its durability and strength, has proven to grow well in erodible hill country (Gea and Shelbourne, 2006). *Corymbia maculata* is relatively frost tender but may be suitable for planting on slopes throughout warmer areas of the North Island (Gordon et al., n.d.). *Corymbia maculata* yields a valuable, heavy, hard, durable, strong and decorative timber, but if heartwood is targeted may require relatively long rotations on account of its wide sapwood band (Satchell, 2015c).

Nothocalyptus

Lastly, *Eucalyptus microcorys* (tallowwood) is renowned as "an excellent timber species" (Hocking 2006c) with a highly ground-durable timber. Tallowwood is the only species in a unique subgenus and has proven to perform well only on warmer sites in New Zealand (Gordon, 2007), with considerable promise for producing high volumes of extremely durable timber in warmer, more sheltered areas of the North Island (A. Gordon, pers. comm). *Eucalyptus microcorys* is "remarkably free of insect pests and diseases in New Zealand" (Hocking, 2006c) but is highly susceptible to snow damage, which causes toppling and snapping of stems even once trees are five to six metres tall (Cairns, 2012). Strong winds also cause stem breakages.

Milling and marketing

High quality plantation-grown timber has been available in the New Zealand market for some time and fetches good prices (P. Davies-Colley, pers. comm).

One of the key issues in terms of market development for eucalyptus timber in New Zealand is the lack of consistent supply of timber into the market, primarily because "instability in supply affects consumer demand and pricing arrangements"

(Trost, 2005). Until there is a sufficient resource being grown, markets will not stabilise.

Issues with grade recoveries from the plantation resource have largely been overcome in New Zealand. Sawn recoveries from eucalypt are improved by sawmilling as soon as possible after harvesting (Trost, 2005; Satchell 2015), because logs tend to split at the ends over time, reducing grade recoveries. Therefore co-ordinating the rate of harvesting with sawmill demand is critical to ensure grade recoveries and value are optimised, with careful transport scheduling required along with removal of logs from the harvesting site as soon as practicable (Trost, 2005). Sawmills usually have sprinklers in place or coat the ends of logs with wax emulsion end grain sealer to limit further splitting (J. Fairweather, pers. comm).

Younger, smaller logs have greater levels of internal stresses than older, larger logs and "mills require logs with a small end diameter of at least 300 mm." (Trost, 2005)

Monocalypt eucalypts are renowned for ease of sawmilling, with minimal growth stresses and compression wood, easy drying and processing and with good wood properties (Hocking, 2010a). The ash group eucalypts are more difficult to saw and process than the stringybarks and the timbers are generally inferior, with none rated as durable (Hocking, 2010a). *Eucalyptus fastigata* is regarded as the best milling ash eucalypt producing good quality, blond timber (Hocking, 2010a), but somewhat lacking in surface hardness.

Uses for ash eucalypt are limited to furniture, joinery and sliced veneer because hardness is not sufficient for applications such as flooring that require hard wearing properties (Davies-Colley, 2006). However, anecdotes suggest that hardness need not limit these species from flooring applications (Tantrum, 2006), although value would likely reduce as softness increases (Satchell, 2015b).

Eucalyptus regnans and *E. delegatensis* can be milled with minimal degrade, provided the drying process is slow (Tantrum, 2006; Satchell, 2010).

Stringybark species, on the other hand, "produce a premiere hardwood timber" (Satchell, 2013b). The timber dries readily with little shrinkage or distortion, with excellent machining properties, yielding a medium-density honey-blonde timber that is stable in service and with very good surface hardness, suitable for applications such as flooring (Satchell 2013b). Stringybark timber also has good durability for applications such as untreated decking and outdoor furniture (Satchell, 2013b). The sapwood band is resistant to lyctus borer and is very narrow at only one to two centimetres, an important but often overlooked quality of these species (Satchell, 2013b). An additional bonus is that little colour change occurs between heartwod and sapwood, so for internal applications sapwod can be included (Satchell, 2013b).

A sawmilling and market value study demonstrated the commercial potential for solid timber production from short rotation *Eucalyptus nitens*, (Satchell, 2015). However, drying degrade remains an issue for some trees even where slow drying is undertaken to reduce degrade (Satchell, 2015).

There is also a potentially high demand for ground durable eucalypt hardwood in New Zealand, in particular for posts and poles used in vineyards, kiwifruit orchards, organic farms and general farm use (Palmer, 2013b). A minimum of 500,000 posts a year are needed in South Island vineyards alone (Palmer, 2013b). Power poles and cross-arms for power poles, railway sleepers and construction timber for rail bridges and wharfs where strength and durability are required, offer market opportunity for ground durable eucalypt produced in New Zealand (Palmer, 2013b).

Fir, silver

The silver firs are a large group of species in the *Abies* genus. In their natural environment they become very large trees that "occupy relatively cool, moist sites at middle to high elevations in mountainous areas" (Miller & Knowles, 1989). Firs are climax species and in their natural environment regenerate within the existing forest structure, so have slower early growth characteristics compared with pioneer or fire-succession species (Miller & Knowles, 1989).

Species in the *Abies* genus are very healthy in New Zealand with many fine specimens existing (Miller & Knowles, 1989). However, *Abies* has been neglected by foresters and researchers in New Zealand, despite some species having good growth rates (Miller & Knowles, 1989; Low, 2011). Silver fir produces a general purpose softwood timber much like radiata pine, which, along with other qualities such as good health and tolerance of a wide range of sites, justify its place as a "contingency species" in terms of biological risk to the radiata pine resource (Miller & Knowles, 1989). Because of slower initial growth rates than radiata pine, silver fir would not be expected to be competitive on many sites and on shorter rotations, but on highly erodible hill country longer rotations that produce similar annualised volumes of wood may have considerable appeal to growers and investors.

Siting and growth

Although comprehensive provenance trials were planted between 1957 and 1968 across 19 sites, these were subject to neglect and as a result the information these have provided to date is limited (Low, 2011). The main trials in the series were sited at Hawkes Bay and North Canterbury (Miller & Knowles, 1989). Despite general neglect such as trees being swamped by rank grass and gorse (Miller & Knowles) these trials demonstrated the considerable potential *Abies* spp. hold for plantation forestry in New Zealand, with impressive mean annual increments of 30 cubic metres per year and very good health (Low, 2011). *A.grandis* (grand fir) and *A. concolor* (white fir) have generally survived and grown well in the trials and although only planted at two sites, the best *Abies religiosa* (sacred fir) outgrew all other species.

Poor establishment in the historical trials is also attributed to lack of mycorrhiza (Low, 2011), an issue easily addressed using modern nursery practices. The slow initial growth in the original trials could also be potentially addressed using modern practices such as application of nitrogen fertiliser and herbicide releasing of young trees from grass and other competing weeds, until the trees have formed strong leaders (Miller & Knowles, 1989). These are standard practice now for species such as redwood that also had poor and slow establishment historically, but now have good survival and early growth (Libby, 2007).

Growth rate for *A. grandis* in New Zealand is comparable with Douglas fir (Miller & Knowles, 1989). Health is excellent compared with Douglas fir, with *Abies* species carrying up to 10 years of living foliage (C. Low, pers. comm), compared with only 1 - 3 years foliage carried on Douglas fir as a result of Swiss needlecast disease (Miller & Knowles, 1989).

Unimproved seedlines imported from North America for both *A. grandis* and *A. concolor* "had good form, with straight stems, regular branching and few forks". Miller & Knowles (1989) suggested that a breeding programme should be established as grafted seed orchards so the best provenances could be developed as a contingency. However, this has not been undertaken to date.

The most promising *Abies* species for lowland New Zealand conditions appears to be *Abies grandis*. Provenance does not appear to be an issue with siting the species and with no obvious latitudinal trend (Low, 2011). In lowland sites *A. grandis* grows better than *A. concolor*, which may be better suited to higher elevations. *A. concolor* may be able to sustain higher stockings than other species (Low, 2011) because of its dense crown and narrow pyramidal form. These two species hybridise naturally where their elevation preferences meet and one *A. concolor* seedlot that may have been collected from such a hybrid swarm in its natural range performed better across all sites than the other *A. concolor* seedlots (Low, 2011). *Abies grandis* tolerates moderate exposure and prefers well distributed rainfalls above 1000 mm, but will grow in drier climates (750 mm annual rainfall) (Miller & Knowles, 1989). *Abies grandis* is less tolerant of exposure than *A. concolor*, whereas *A. pinsapo* (Spanish fir) tolerates drier sites and periodic strong winds (Miller & Knowles, 1989). Although *A. religiosa* has the fastest growth rates, being frost tender it is only suited to low-elevation sites (Miller & Knowles, 1989), with good examples at the Longmile Rotorua (C. Low, pers. comm). *Abies magnifica* (Red fir), on the other hand, being a high elevation species is not tolerant of lowland sites where it appears to suffer from root rot (C. Low, pers. comm).

Fir species are wind-tolerant and tolerant of bony soils as found in exposed erodible steeplands (C. Low, pers. comm). However, A. concolor may tolerate greater wind exposure than A. grandis, with its narrower crown and finer-branched architecture. The Hanmer trial site is particularly boney and exposed to Canterbury nor-wester winds and A. concolor has performed particularly well there, with no windthrow (C. Low, pers. comm). True fir species appear to be more wind tolerant than Douglas fir and with superior growth rates (C. Low, pers. comm).

Management and silviculture

The suggested silvicultural regime for New Zealand is for an initial stocking of 1667 stems/ha (3m x 2m), thinned at about 17 years of age when the top height is 14 m to 500 stems/ha, for a rotation length of 40 years or more (Miller & Knowles, 1989).

Stocking can be high for *Abies grandis* and *A. concolor* because of exceptional foliage health and shade tolerance, resulting in a high basal area (Low, 2011). These species have narrow conical form with small abundant branches that are shade-tolerant, lending them to regimes with longer rotations and higher stocking rates (Low, 2011). At age 47 in Gwavas forest Hawkes

Bay, *A. grandis* had standing volumes of 1500 cubic metres at an average stocking of 400 stems per hectare, a third higher than for Douglas fir of the same age (Low, 2011). The largest trees had diameters of over 80cm and Low (2011) suggested that stocking should be higher for better volume production, because superior volume growth at this age was exhibited by stands at 600 stems per hectare.

Weed potential

Although on suitable sites regeneration has sporadically taken place under parent stands, no *Abies* species has shown any tendency to spread more widely (Miller & Knowles, 1989).

Timber

In North America, silver fir species are prominent producers of both sawn timber and pulp (Miller & Knowles, 1989).

Although the timber has traditionally not been as highly regarded as Douglas fir (Low, 2011), strength properties are only slightly below those of Douglas fir and stiffness values are second only to Douglas fir in terms of Western North American softwood species (WWPA). However, data has not been published on timber properties for New Zealand material. In North America fir timber is marketed under the generic species combination "hem-fir" (an umbrella term for species with similar wood) comprising Western hemlock and five of the true fir species (WWPA).

Fir timbers "are soft, whitish in colour and easily worked to a good finish, taking paint and varnish well" (Miller & Knowles, 1989). Fir species have become preferred construction timbers because of the ability to hold nails and screws well with a resistance to splitting, a low propensity for splintering when sawed and a straight-grained, non-resinous, fine-textured, stiff and strong timber. (WWPA).

Fir timber is not resistant to decay, but "as roundwood they will absorb fluid preservatives applied under pressure, or using a hot and cold impregnation method" and "treated in the round they make serviceable posts and poles" (Miller & Knowles, 1989). Sawn silver fir is easily treated with preservatives (AWPA) and treated fir timber is commonly used for structural decking on account of its strength and beauty (WWPA).

Although not as strong as the Douglas fir-larch species combination sold in North America, silver fir has a very high modulus of elasticity (MOE) for its weight and has excellent stiffness-to-weight ratios (WWPA). Because of its low natural durability, for structural applications the H1.2 hazard class (NZS 3640:2003) specifies treatment with boron to 0.4% BAE retention for softwoods. Boron preservative treatment provides "deep penetration and hence full protection" for fir species (Lloyd, 1995).

Natural stands of fir are an importance source of pulpwood (Miller & Knowles, 1989).

Kauri

Kauri (*Agathis australis*) has long been regarded as the Lord of the Forest, the dominant tree species of the natural rainforest in northern New Zealand, with diameters of 6 m recorded (Bergin & Steward, 2004). Most kauri forests have been cleared and the small remaining areas in mature forest are now reserves (Bergin & Steward, 2004).

Kauri forms extensive root systems with both deep "peg" roots or "sinkers" that descend from lateral roots and provide anchorage, along with an extensive network of lateral roots and a mat of fine feeding roots (Bergin & Steward, 2004). Fusion of lateral roots has been observed between adjacent trees in mature kauri and stumps may consequently stay alive for considerable periods of time (Bergin & Steward, 2004).

Siting

Kauri requires warmth to grow well and does not tolerate heavy frost (Bergin & Steward, 2004). In particular, the shoots of young plants can be damaged, causing multiple leaders to develop (Bergin & Steward, 2004).

Kauri prefers moist fertile soils and is not likely to survive on drought-prone infertile ridgetops (Bergin & Steward, 2004). Application of fertiliser can improve growth where soils are infertile (Bergin & Steward, 2004). Mycorrhizal associations are found in natural kauri forests. These have been investigated and may improve phosphate absorption by roots (Morrison & English as cited in Bergin & Steward, 2004).

Kauri "should be planted on open sites only if these are sheltered and warm" (Bergin & Steward, 2004). Because nursery raised seedlings tend to have poorly developed root systems, planted seedlings tend to be highly susceptible to drought for the first two years after planting (Bergin & Steward, 2004). Site preparation needs to be good and competing plants removed for up to 5 years (Bergin & Steward, 2004).

Small seedlings require shade and shelter, but saplings prefer full sunlight. Side shading is recommended for establishing kauri, such as provided by a manuka nurse crop established before line planting of kauri (Bergin & Steward, 2004). This protects young plants from wind and frost. However, releasing may be necessary to ensure the kauri is not overtopped until at least 1-2 m high (Bergin & Steward, 2004).

Management and silviculture

Seedlings tend to develop a strong taproot and nursery systems need to encourage development of a fibrous root system (Bergin & Steward, 2004). Kauri is usually grown in containers and although kauri can be raised as bare-rooted seedlings, taproots are damaged by mechanical undercutting (Bergin & Steward, 2004). Kauri can be grown from cuttings (Bergin & Steward, 2004). The cost of 50 cm high two year stock in containers was $3-4 per seedling in 2004 (Bergin & Steward, 2004), which is high for plantation forestry requiring high initial stockings.

On a good site, similar volumes might be expected from 60 year old kauri as 40 year old cypress and individuals might be expected to achieve 40 cm diameter and 20 m height in 50 years (Bergin & Steward, 2004). Although some plantations established on fertile sheltered sites with good soil moisture can achieve diameter increments of greater than 10 mm per year if given sufficient space, dense stands with stocking rates of 1000 stems/ha might be required to achieve good branch suppression, with an average diameter of 20-30 cm at 60 years old and a mean annual increment of 20 m^3/ha for the first 40 years (Bergin & Steward, 2004). If thinned down to 700 stems/ha at 60 years the residual trees might be a harvestable size once over 100 years old. Trees with diameters of 90 cm can be expected to contain 2 m^3 of heartwood in the lowest 6 m log (Bergin & Steward, 2004).

Poor performance of trial kauri plantations is often attributed to lack of adequate releasing from competing vegetation (Bergin & Steward, 2004).

Form pruning may be required to remove double leaders (Bergin & Steward, 2004).

Damage to kauri seedlings and saplings by goats, deer and possums has been observed (Bergin & Steward, 2004).

Pests and diseases

Kauri has few problems with insects, but a serious disease, believed to have been introduced into New Zealand from overseas has become established – kauri dieback disease *Phytophthora agathidicida*, formerly known as *Phytophthora* taxon *Agathis* (PTA). This is believed to have arrived on military equipment in the 1950's that was repatriated from the pacific after World War II (Brown, 2015). The disease is now widespread through Kauri's natural range and continues to spread, with no treatment available (Brown, 2015).

Kauri dieback can kill trees and seedlings of all ages and is spread primarily by movement of infected soil such as on footwear or machinery or by animals such as feral pigs (Bellegard, 2012; Brown, 2015).

Timber

The heartwood of mature kauri is "one of the finest softwood timbers in the world" (Bergin & Steward, 2004). Although sapwood has some of the appearance qualities of heartwood, it is lighter in colour than the heartwood, is not as dimensionally stable, lacks durability and is susceptible to *Anobium* borer (Bergin & Steward, 2004). Sixty-six year old trees from a plantation in New Plymouth were found to contain mainly sapwood (Bergin & Steward, 2004). Stiffness values were higher than for old-growth kauri and radiata pine and wood quality did not vary much between the pith and outer wood (Bergin & Steward, 2004).

Larch

Larix species (larch) are deciduous northern hemisphere subalpine conifers. Both European larch (*Larix decidua*) and Japanese larch (*Larix kaempferi*) have been widely planted in New Zealand, with 3400 ha in plantations in 1988 (Miller & Knowles, 1988). Larch has proven to be a long lived species in New Zealand and can grow into large trees (Miller & Knowles, 1988).

European larch was the major species planted in afforestation programmes in New Zealand in the early 20th century, however it fell into disfavour primarily because of radiata pine's superior growth rates and treatability (Miller & Knowles, 1988). Unfortunately, high initial stockings followed by neglect in these early plantings were not a recipe for success and produced "stands of crowded, poorly crowned trees" (Miller & Knowles, 1988). Japanese larch was not planted as extensively, with small-scale plantings made in Canterbury, Nelson and the central North Island in the 1950's (Miller & Knowles, 1988). European larch can have poor stem form (M. Dean, pers. comm).

Management and silviculture

Larch is easy to grow in the nursery and offers good early growth rates of between 0.5 m and 1.0 m per year for the first 5-6 years (Miller & Knowles, 1988).

Although early height growth rates are often impressive, this may not carry through to high volumes in later years compared with Douglas fir (Ledgard, 2007b). This is because larch is both space demanding and light demanding, so should be thinned regularly to ensure the stand does not become overcrowded (Miller & Knowles, 1988). Recommended final crop stocking for larch is 400 stems per hectare (Ledgard, 2007b), which results in production of lower volumes of wood compared with Douglas fir. Wood properties and appearance is similar to Douglas fir, with excellent toughness and stiffness, but because Douglas fir is less light demanding and also more site tolerant it has become the more favoured species in New Zealand for plantations (Ledgard, 2007b).

Thirty year old trees are typically 16-20 m high with 25-30 cm diameters at breast height (Miller & Knowles, 1988). Sixty to eighty year old trees reach 35 m height and 40-50 cm in diameter (Miller & Knowles, 1988). Unfortunately, growth and yield for larch plantations has not been quantified because older stands have consistently been grossly neglected and performance data would be misleading (Miller & Knowles, 1988). However, Birch (as cited in Miller & Knowles, 1988) concluded that "larch grows well in New Zealand" and at Whakarewarewa Forest a 41-year-old, unthinned stand yielded 450m^3/ha on clearfelling.

Fifteen year old hybrid larch production thinned for posts yielded 1762 posts and 1950 stays, amounting to 83 m^3 per hectare, leaving a residual volume of 94 m^3 per hectare (Miller & Knowles, 1988). The resulting volume growth and production levels for this stand could perhaps be measured if the stand still existed.

Weeds must be managed well, especially overtopping brush weeds such as broom, because larch does not suppress such weeds (Miller & Knowles, 1988).

Production thinning may be possible for roundwood and firewood (Miller & Knowles, 1988). Miller & Knowles (1988) suggested that initial stocking should be 1250 stems per hectare (4 m x 2 m), reduced to 400 stems/ha once the trees are 8-10 m high, aiming for a final stocking of 200 stems per hectare on a 60-80 year rotation. Sheep and cattle may be grazed in larch once trees are big enough to withstand damage (Miller & Knowles, 1988).

Siting

Although a tough tree and capable of surviving in a wide range of sites, larch prefers sheltered slopes in higher rainfall areas for good growth and form, primarily because larch flushes early and late frosts can damage spring growth (Ledgard, 2007b).

Larches are deep rooting trees and grow well in deep fertile clay soils, but do not like poor drainage (Miller & Knowles, 1988). Windthrow is uncommon (Miller & Knowles, 1988). European larch can productively grow at moderately high altitudes of up to 900 m, whereas Japanese larch is limited to 600 m (Miller & Knowles, 1988). Larch requires shelter from excessive wind and sufficient spring moisture for growth and although very frost hardy in winter, is very susceptible to frosting in spring at the time the trees flush (Miller & Knowles, 1988).

Provenance trials of both European and Japanese larch showed little variation between provenances of Japanese larch, but with superior provenances of European larch identified (Miller & Knowles, 1988). Japanese larch grew better than European larch from Rotorua to Nelson whereas European larch grew best in the eastern and central regions of the South Island from North Canterbury to Western Otago (Miller & Knowles, 1988). Two hybrid clones, crosses between European and Japanese larch originating from Denmark where artificial hybrids were produced from select quality parents, were included in the New Zealand progeny trials (Miller & Knowles, 1988). These produced straighter trees, superior growth and greater volumes than both pure species at all sites, this superiority being more pronounced in northern sites (Miller & Knowles, 1988).

Hybrid larch progeny has been produced in New Zealand from selected parents, but performance of these was not reported by Millar and Knowles (1988). Growers report excellent growth rates from hybrid larch (G. Baldwin, pers. comm; A Roulston, pers. comm).

Although larch is considered to be a relatively easy rooting conifer species, propagation of clonal hybrids in Europe encountered high production costs combined with plagiotropy and decreasing rooting quality over time. This has been subsequently improved by using only juvenile stock plants and renewing these every few years (Paques, 2013).

Weed potential

European Larch has been found to spread freely by natural regeneration in some high country locations in the South Island, but spread is uncommon in the North Island (Miller & Knowles, 1988). Japanese larch has spread in the immediate vicinity of parent stands at Hanmer (Miller & Knowles, 1988). Larch has light seed which can be readily blown some distance giving rise to wilding spread (Ledgard, 2007b). In the high country survey from the early 1980s "this species had the highest incidence and distance of spread of all the more common plantation species, contorta and Scots pine not included" (Ledgard, 2007b). Ledgard (2007b) suggested that larch "should not be planted upwind of lightly vegetated or lightly grazed land". Wilding potential is higher for inland drier areas but it may not deserve its reputation as a vigorous spreader, being palatable to grazing animals and susceptible to late spring frosts (N Ledgard, pers. comm).

Pests and diseases

Larch canker *Lachnellula wilkorrunii* is a major disease of larch in Europe but is not present in New Zealand (Miller & Knowles, 1988). However, Japanese larch and Japanese larch hybrids have resistance to the disease (Wunder, 1973).

Timber

Larch wood has excellent stiffness and toughness with a moderately high density of 560 kg/m^3 at 12% moisture (Ledgard, 2007b). Strength and stiffness is high and at least as good as Douglas-fir. Larch has been approved as a framing timber since 1975 (Miller & Knowles, 1988).

Larch has a high proportion of heartwood even as relatively young trees. Heartwood from New Zealand material is not durable in ground contact and larch heartwood is resistant to impregnation with preservatives (Miller & Knowles, 1988).

Sawing is straight forward and although care is required in seasoning larch air dries readily (Miller & Knowles, 1988).

Larch is an attractive decorative timber with a prominent grain. Knots are small, numerous and tight, although "the timber has a slight tendency to splinter and 'pick out' at knots during machining" (Miller & Knowles, 1988).

Larch kraft pulps have high tearfactor and reasonable tensile strength so is particularly suitable for packaging papers (Miller & Knowles, 1988).

Manuka

Mānuka is not a plantation forestry species for timber, but there is considerable interest in plantations for producing honey.

There has been international acceptance of the medicinal properties of mānuka honey, which holds a significant price premium in the market depending on the activity rating (Orme, 2017). As a plantation investment, costs associated with planting mānuka are higher than for managing an existing stand and expected rates of return will be lower (Orme, 2017). By adding in carbon to the equation however, mānuka plantations could potentially produce a positive internal rate of return (Orme, 2017).

Because climatic conditions influence flowering success, honey production is subject to annual variability (Orme, 2017).

As a primary coloniser, mānuka naturally dies out as larger trees over-grow the canopy (Orme, 2017), so retaining the mānuka crop would require active management. Another option is to interplant plantation forestry species with mānuka to increase the stocking of trees for improved erosion mitigation, along with production of honey from the mānuka until overshadowed by the timber species. Mānuka could provide a source of income during the establishment phase of the longer term timber crop, while also acting as the nurse for improved form and establishment of the timber crop.

Native species such as tōtara, kauri and beech benefit from the protection a mānuka nurse crop provides when planted on exposed, steep eroding hillsides.

Pine, radiata

The focus of this report is on alternative species to radiata pine that offer productivity while at the same time provide superior erosion prevention to radiata. However, radiata pine could potentially be managed to provide improved erosion prevention in red zoned steeplands.

Standard-practice radiata regimes such as planting 800 stems per hectare and clearfelling in 25 years are not likely to continue on red zoned erodible land because of the risk for significant erosion to occur. The risk for steep slopes to erode significantly increases every 25 years when the trees are harvested, for a period of time called the "window of vulnerability".

Radiata pine, being by far the most widely planted plantation forest species in New Zealand, is the obvious benchmark for comparing other species with. The ratings for each species provided in this report offer a means for comparison.

The issues with radiata pine that make alternatives superior in terms of erosion prevention include:

1. Radiata pine's roots rapidly decay so root soil-holding capacity is rapidly lost after harvesting;
2. Radiata pine is a commodity timber species and returns dictate that clearfell harvesting is necessary to be economically viable;
3. Optimum rotation length is 25 years, therefore the window of vulnerability opens for a period every 25 years.

Nevertheless, there are options available to growers to reduce the risk for erosion in steepland radiata plantations. These include:

- replanting harvested areas immediately with a high stocking of trees, for example 2000 stems per hectare;
- growing radiata pine on longer rotations.

- growing radiata pine under a continuous cover regime whereby coupes or single trees are harvested to maintain a canopy.

It should be noted that although roots rapidly decay after clearfell harvesting, a study of root systems in 18 year old radiata pine in New Zealand showed that root grafting occurs and root systems of thinned trees remain alive after harvesting (Will, 1968). Root grafting begins when radiata pine is about ten years old and increases rapidly from that age to at least 25 years of age (Wood & Bachelard, 1970). Therefore partial harvesting may offer high levels of erosion mitigation.

Poplar

Poplar and willows are widely planted in pastoral hill country for erosion control. Poplar also has potential as a plantation forestry species and as silvo-pastoral plantings in the presence of stock.

If large areas of erodible hill country are to remain in pastoral production in New Zealand, there is potential for poplar agroforestry to create "a large, economic resource of pruned poplar sawlogs" , along with "contrasting fibre and wood characteristics to those of pine" suitable for integration with pastoral farming as a viable crop that complements the radiata resource (Wilkinson, 2000). However, eighteen years later the question remains whether sufficient research has supported realising Wilkinson's (2000) vision of a future role for poplar whereby "high value products can be identified and grown".

Poplar is currently planted for erosion prevention in pastoral land with the primary purpose of retaining pastoral production. Wide spacing between trees does not cause significant shading of pasture (McIvor et al. 2011). Wilkinson (2000) recommended a stocking of 100 stems/ha for agroforestry in order to balance timber production with pastoral production. Where timber production is prioritised under an agroforestry regime, the stocking can be increased to 200 stems/ha (Wilkinson, 2000). Farming poplar for carbon also offers hill country livestock farmers an opportunity to reduce erosion risk at low cost, with the requirement being for 30% tree canopy cover, potentially fulfilled with as few as 40 space planted trees per hectare (Eyles, 2010).

Poplar root systems exhibit strong extensive growth and bind soil effectively, with root grafting between adjacent trees (McIvor et al. 2011). However, little data is available on how effective "spaced" poplar is in controlling erosion (McIvor et al. 2011). Knowles (2006) suggested that "the low stockings often employed for poplar pole planting may make them less effective for erosion control than commonly thought", while a 1992 study showed that mature spaced trees, where well maintained, "reduced soil erosion by about 60% to 70%, while poorly maintained poplar plantings had minimal effect." (Hocking, 2006a). Root mass is proportional to tree diameter and high planting densities are required for younger poplar trees to develop a structural root network sufficient to control erosion (McIvor et al. 2011). Once trees are mature, close-tree planting will reduce erosion by 90%, compared with 70% for spaced-tree planting on erodible pastoral land (McIvor et al. 2011). Although conservation poplar plantings do not ensure erosion will be prevented, with spaced plantings of poplar, production losses attributable to landslides could potentially be significantly reduced once the trees reach diameters greater than 30cm (McIvor et al. 2011). Thus, wide spaced trees would take longer to achieve high levels of soil binding than where closer planted; and where erosion potential is severe, a closed canopy tree cover is recommended (McIvor et al. 2011).

Establishment

Poplar is easily established in the presence of stock by using large poles and protecting these with plastic sleeves. However, this method is suitable only for establishing poplar in the presence of stock rather than establishment of high tree stockings. In the absence of stock, high stockings are achieved by using small stakes or forestry "wands" (Wilkinson, 2000). Rooted cuttings may play an increasingly important role in woodlot establishment, especially in drier sites (Wilkinson, 2000) where deep planting is required for trees to access permanent soil moisture and establish successfully (Hunter and McIvor, 2008). Two to three years are required from establishment until livestock can be re-introduced (Wilkinson, 2000) and regular releasing from grass competition for at least the first year is required.

Siting

Poplar requires at least moderate soil moisture (Wilkinson, 2000). Large areas of New Zealand’s hill country, including much of the East coast of both islands is not suitable for stabilising with poplar and willow because of inadequate soil moisture during summer (Van Kraayenoord and Hathaway, 1986). Poplar only grows in low rainfall areas where the water table is high (Wilkinson, 2000), so on hillsides in summer-dry regions, planting should be restricted to channels, tunnel gullies and seepage areas (Wilkinson, 2000).

Poplars prefer and grow best in fertile, moist and friable soils (Van Kraayenoord and Hathaway, 1986; Hunter and McIvor, 2008). Because poplar prefers deep soils, growth rates tend to decrease going up the slope (McIvor et al. 2011). Poplars are not happy on exposed eroding hillsides (Knowles, 2006), preferring alluvial terraces and moist valley bottoms (Wilkinson, 2000). Desiccating winds are damaging (Van Kraayenoord and Hathaway, 1986) and trees become deformed and stunted where planted on exposed upper slopes and ridges (Wilkinson, 2000). Some poplar cultivars such as black poplar hybrids cope with some wind exposure, while balsam poplar hybrids offer improved possum resistance but where exposed to wind have poor form (Wilkinson, 2000).

Poplar can be grown to 800 m altitude without frost damage (Van Kraayenoord and Hathaway, 1986). In their deciduous state poplar can tolerate heavy frosts, but some cultivars may suffer frost damage to the growing shoot caused by late spring and summer frosts.

Poplar is a fast growing tree, but site adaptability for the range of poplar cultivars grown in New Zealand is not yet fully understood (Wilkinson, 2000). The Forest Research Institute modelled growth rates for pruned trees and found that on good sites poplar can produce over 400m^3/ha volume production at 200 stems/ha on a 20 year rotation and over 500m^3/ha on a 30 year rotation. This reduces to 128m^3/ha for a 20 year rotation on a poor site and 161m^3/ha for a 30 year rotation on a poor site (Wilkinson, 2000). This data clearly shows that site is important for volume production, which increased by a factor of 3 from a poor site to a good site.

Silviculture

In order to produce knot-free timber pruning is essential (Wilkinson, 2000). Pruning for timber requires an initial form prune before year two and for clearwood requires interventions from year two to four, with lifts every two years until the lifts reach between six and eight metres (Hunter and McIvor, 2008), best achieved by retaining 50% of the height of the tree as green crown (Wilkinson, 2000). The aim is to restrict the knotty core to a central diameter of 150 mm over pruned branch stubs, but epicormic shoots that follow pruning can be an issue (Wilkinson, 2000). Poplar prolifically produces epicormic shoots when pruned, which need subsequent removal. Pruning is best undertaken in Autumn rather than spring to minimise epicormic shoots (M. Hunter, pers. comm).

Weed potential

Although poplar has the potential to become a serious weed species where breeding populations are established, very few populations of poplar in New Zealand are established and self-perpetuating (i.e. naturalised), likely because the widely distributed clones are either unisexual or non-breeding hybrids, limiting spread by seed (Wilkinson, 2000). Breeding programmes thus focus on producing male cultivars (Wilkinson, 2000).

Timber

Because of poplar's rapid growth rate, timber suitable for a range of products can be produced in relatively short rotations (McIvor, 2010).

Poplar wood has low to medium density, an even pale white colour, indistinct growth rings and a fine texture (Wilkinson, 2000). The wood has an attractive lustre where clear coated (Williams et al. 1986). The heartwood can be difficult to distinguish from the sapwood and the wood is odourless (Wilkinson, 2000). The light colour of the timber is appreciated by the appearance market but low surface hardness detracts from use in furniture making, despite the wood's attractive appearance (Wilkinson, 2000).

Poplar wood can be used for solid timber applications, chip and paper pulp (Hunter and McIvor, 2008). Applications include decorative veneers, plywood, construction, furniture and wood-based composites (McIvor, 2010). Globally, emerging applications for poplar include engineered wood composites, chemical extracts and bio-energy (McIvor, 2011). Specialised markets exist in Asia, where poplar is an accepted timber species (Wilkinson, 2000).

High quality pruned logs have excellent potential for sliced and peeled veneer (Williams et al., 1986).

Poplar has good strength properties in relation to density (Hunter and McIvor, 2008; McIvor, 2010). The New Zealand breeding programme has aimed for a basic wood density of at least 360 kg/m^3 (Wilkinson, 2000). Although this is lower than for radiata pine, there remains potential for selecting higher density clones for sawn timber production (Wilkinson, 2000). Within-cultivar density varies little between region, site and position in the tree (Wilkinson, 2000), suggesting that very even strength properties can be expected, possibly an advantage when characterising strength properties for use in structural products. Although the product would be inferior to and in most cases be in direct competition with radiata pine (Williams et al., 1986), structural products requiring good appearance properties such as exposed rafters, posts and beams along with laminated structural products may hold some market potential.
Poplar wood has low natural durability. Poplar is not listed for structural applications in NZS 3602:2003 *Timber and Wood-based Products for Use in Building*, so durability performance would need to be demonstrated before structural products could gain acceptance in the New Zealand construction market. Although boron penetration has been found to be satisfactory for protection against insect attack in protected interior situations (Wilkinson, 2000), protection to the H1.2 hazard class required for structural applications would require demonstration of durability performance equivalent to H1.2 treated radiata (T. Singh, pers. comm). The H1.2 hazard class applies to timber used in situations protected from the weather, where there is also a risk of moisture content conducive to decay (NZS 3640:2003 C6.1). Pressure treatment of poplar with boron has provided unsatisfactory penetration results (T. Singh pers. comm) but two months of boron diffusion provided boron retention well above the requirements of the H1.2 specification for both 25 mm and 50 mm thick boards (Williams et al. 1986).

In-grade testing of poplar has shown that working stresses were similar to medium-density radiata pine visually graded to No. 1 framing (Wilkinson, 2000), provided adjustments were made for density; and critical joints had additional fixing (Wilkinson, 2000). Therefore, some evidence-based research would be required before introducing poplar into the building code as an acceptable solution for structural applications.

Poplar pulps have excellent papermaking qualities suitable for fine paper production (Williams et al., 1986) and pulps with "high bulk, moderate strength properties, and excellent optical properties" can be produced from poplar (Richardson and Jones as cited in Wilkinson, 2000), offering an excellent addition to a softwood base of radiata pine (Williams et al., 1986). However, studies and deployment in New Zealand to date have been limited.

Pressure treatment of dry sawn timber with CCA salts has been shown to provide variable penetration (Williams et al. 1986). However, poplar appears to have not been tested using contemporary CCA treatment methods such as steam pre-treatment under pressure to condition green timber for treatment. Nevertheless, CCA preservative treatment of roundwood was found to be satisfactory (Williams et al. 1986) with Wilkinson (2000) reporting that "CCA-treated poplar has been widely used for fence battens and gates". However, poplar fencing may not hold nails and staples as well as radiata pine (Williams et al. 1986).

Poplar saws easily (Williams et al. 1986) but sawn timber recoveries are lower than for radiata pine, with the main timber defect being knots (Wilkinson, 2000). Tension wood is present which may cause wooliness and collapse in sawn boards (Williams et al., 1986). Kiln drying of poplar timber from green can be achieved in two to three days without degrade (Wilkinson, 2000). Machining properties are inferior to radiata pine (Wilkinson, 2000). Surface coatings are easily applied and poplar takes an even stain (Wilkinson, 2000). Some poplar cultivars have been evaluated in New Zealand for wood density, sawing, machining and drying properties (Wilkinson, 2000).

There is an export market for the logs, which may attract a slight premium over radiata pine (Hunter and McIvor, 2008) and "there is a small but growing market for poplar timber." (Eyles, 2010).

Redwood, coast

Where there is a high risk of post-harvesting landslides, redwood has the potential to become an important erosion-control forestry species (Phillips et al. 2012). This is because of good growth rates in early years, the ability to produce many fine lateral roots and the ability to coppice once the tree is removed (Phillips et al. 2012).

Redwood is unique among conifers in that it produces coppice growth from roots and stumps, so regenerates prolifically in cutover stands (Berrill & O'Hara, 2007). This gives redwoods exceptionally high soil stabilisation properties (Libby, 2006). Redwood offers good erosion control in steep country because the roots remain alive after harvest and continue to reinforce the soil (Burdon, 1975 as cited in Meason et al. 2012; Phillips et al. 2012; Silcock, 2008; Webster, 2007). Roots also graft with neighbouring trees, forming a continuous network, providing additional reinforcement (Wallwork & Rapley, 2009; Clinton et al., 2009). However little information is available on how many years it takes for young trees to form a live network of roots (Clinton et al., 2009).

Redwood for mitigating erosion

Because stumps coppice, rapid restoration of the forest canopy takes place (Burton, 1975 as cited in Meason et al. 2012) and re-establishment costs are minimised (Webster, 2007). However, because regeneration tends to be confined to stumps, this can leave large gaps between trees along with a "clumpy" distribution of trees (Berrill and O'Hara, 2007). The coppice also requires silvicultural management to reduce sprouts to no more than 3 per stump (Berrill & O'Hara, 2007).

Because tree canopy functions, such as the ability to intercept rainfall and transpiration, are lost when trees are felled, the ability for redwoods to coppice does not entirely negate the negative effects of harvesting on soil (Madej, M. 2010; Reid & Keppler, 2011 as cited in Meason et al., 2012). Clearfelling significantly reduces live root mass volume even where stumps stay alive, therefore sufficient root cohesion to prevent erosion may take 10-15 years to re-occur after harvesting (Reid & Keppler, 2011 as cited in Meason et al., 2012).

Redwood also has "the ability to produce adventitious roots near the new ground surface when smothered by silt" which "is an additional advantage of redwood over other species if, for example, any surface erosion or landslides were to occur and deposit sediment within a stand of trees" (Marden 1993 as cited in Phillips et al. 2012). Because redwood is good at withstanding flood events and sedimentation below sites where gully erosion is likely, redwood is a good option for planting in flood zones beside tributaries, to filter debris flows before these reach more significant water courses (P. Silcock, pers. comm.).

Phillips et al. (2012) studied the below ground characteristics of young redwood trees in the context of erosion control and found that at 3 years of age redwood compared favourably with radiata pine. Root biomass, total below-ground biomass and total tree biomass were similar for the two species, although "in some situations radiata is more likely to reach a given RCD in a shorter time from planting than redwood, the differences are not expected to be great for trees less than about 6 years from establishment" (Phillips et al. 2012). This is because along with the use of clonal material (R. Coker pers. comm. as cited in Phillips et al., 2012) "recent experience with pre- and post-planting care, in particular good site preparation, attention to nutrient status, and control of competing plants, now results in much better survival and early growth than previous experience" (Libby, 2007).

In warm North Island sites with sufficient rainfall and good soils, redwood growth rates are comparable to those for radiata pine (S. Rapley, pers. comm). However, siting can have a far more significant impact on redwood growth rates than those for radiata pine. In particular, redwood requires medium to high productivity sites with sufficient soil depth. While radiata pine grows relatively consistently across a site with variable soil qualities, redwood will be extremely variable in terms of growth rates (P. Silcock, pers. comm). In particular, eroded gullies with no topsoil or hard clays underlying shallow soils produce poor growth rates, which may be more soil moisture deficit related than fertility (P. Silcock, pers. comm). On lower productivity sites redwood only grows at half the rate of radiata pine during the early years, potentially extending the rotation length to 60-80 years (S. Rapley, pers. comm.). Redwood performs particularly well below steeper eroding land on the lower slopes where there is sufficient topsoil (S. Rapley, pers. comm).

Siting

Redwood can be very productive in terms of annual growth rates, but only if well sited (Libby, n.d.). Redwood is capable of matching the growth performance of radiata pine on warm, moist, sheltered, fertile sites (Webster, 2008). However, redwood is more site-limited than radiata pine and can be "badly affected by chronic winds, particularly if those winds are salt-laden" (Libby, 2007). Brown (2007) described redwood as requiring "a temperate climate, decent soils and regular rainfall". Limitations include heavy frosts, salt spray and strong prevailing winds, although redwood can "withstand occasional gales" (Brown, 2007) and is "surprisingly resistant to toppling and breakage from periodic storms" (Webster, 2008).

Redwood is considered to be a good choice for moist soils in sheltered sites (Thomsen, 2011). Webster (2008) found that best growth rates are found in warm, moist sites in coastal Bay of Plenty, Northland, Waikato, inland Taranaki, the King Country and the East Coast of the North Island. South Island locations suitable for redwood include the Nelson region and sheltered parts of the West Coast (Webster, 2008). Careful site selection would be necessary in the sedimentary soils of the Wanganui hill country exposed to strong coastal winds and seasonal drought (Webster, 2008). Exposed sites in Wairarapa produce wind-affected trees (S. Rapley, pers. comm). Young trees are especially intolerant of exposure and require shelter from strong winds (Knowles & Miller, 1993).

Redwood tolerates periodic storms but is less resilient to persistent prevailing winds, especially where cool or salt laden

(S. Rapley, pers. comm). Exposed ridgetops produce "windshorn" trees of little value (P. Silcock, pers. comm). Slopes exposed to persistent wind produce second rate trees, whereas as little as ten metres down the slope on the leeward side of a ridge produces good quality trees (P. Silcock, pers. comm). To avoid production of different timber types, ridgetops and exposed slopes in redwood plantations could be planted in the extremely resilient giant sequoia.

Redwood has a preference for mild climates and is vulnerable to out of season frosts (Webster, 2008) such as those that occur on the central North Island volcanic plateau (Dean, 2007). Redwood is resistant to snow damage because its thin horizontal branches shed the snow (Cairns, 2012).

Management and silviculture

Because initial stocking tends to be low and plants expensive, establishment of redwood requires attention to quality of planting and clonal tree stock, along with timely releasing, to ensure an evenly stocked forest is established (Mineham, 2009). Newly planted trees have a high soil moisture requirement and weed competition, especially grasses, can seriously impede growth (Knowles & Miller, 1993).

Interim recommendations in 2007 were for a final spacing of four to five metres between trees (Brown, 2007). Knowles & Miller (1993) suggested a final crop stocking of between 200 and 300 stems per hectare with pruning up to 10 m.

Redwood can accumulate large volumes of stemwood per hectare and can grow into very large trees of considerable age with few pests or diseases (Wallwork & Rapley, 2009; Libby, 2006). These characteristics led Dean (2007) to suggest that redwoods could be managed under more innovative regimes than clearfell harvesting. Because redwoods are also shade tolerant they are well suited to being managed under continuous canopy systems (Webster, 2007; Wallwork & Rapley, 2009). Being shade tolerant, coast redwood "can recover from almost indefinite suppression" (Knowles & Miller, 1993). Berril and O'Hara (2007) found that stands thinned to half their original basal area "quickly returned to a similar rate of productivity as unthinned stands, but there were many fewer trees, resulting in greater diameter growth". Dean (2007) suggested that a more structured effort is required "to identify and answer the key 'how to' questions of uneven-aged stand management".

Selective logging of regrowth redwood forest with haulers is common practice in California. However, selective logging is more expensive than clearfelling and taking into account the time value of money it may be difficult to justify on economic grounds alone (S. Rapley, pers. comm) unless log values were to double from current prices (P. Silcock, pers. comm). Pruned plantations on flatter ground could be harvested by extracting every second row, leaving behind half the volume to grow into large buttlogs for a potentially profitable outcome (S. Rapley, pers. comm). One option for steeper country is for tethered harvesting machines to harvest strips of trees (P. Silcock, pers. comm). Importantly, redwoods can be released at any age, i.e. they are never too old for a growth response after removal of adjacent competing trees (S. Rapley, pers. comm).

On sheltered fertile sites volume production can equal that from radiata pine (Knowles & Miller, 1993). Brown (2007) considered New Zealand's conditions to be "better suited to growing redwood than anywhere else on earth". Brown (2007) and Dean (2007) both suggested clearfell rotations of 35 years, with Rydelius (2007) recommending planting clonal stock at 500 stems per hectare and harvesting at 30 years old.

Redwood is pruned to maximise production of high-value clear heartwood. Pruning of redwood encourages production of epicormic shoots, requiring subsequent removal (Brown, 2007). Epicormic shoots are less frequent if pruning is undertaken in autumn rather than spring (Brown, 2008). Pruning redwoods to a small DOS is desirable in terms of clearwood production, but production of epicormics and bark damage around pruned collars can be a problem in younger trees (Dean, 2007). Delaying of pruning until the bark thickens and leaving more green crown in the trees after each pruning lift negates formation of epicormic shoots and has less impact on growth (Dean, 2007). Silcock (2008) suggested that ultra-high pruning would be worthwhile, although anecdotal evidence suggests that pruning may allow entry of a native longhorn borer (Dean, 2007). Thirty-eight year old trees that were pruned four times to a height of six metres and thinned twice down to a final stocking of 398 stems per hectare only produced 32% of timber from the pruned logs that was graded clearwood (Silcock, 2009). The defect core in these trees was 305 mm and averaged 60% of the diameter at breast height (Silcock, 2009), suggesting that silviculture should achieve a small defect core in order to justify pruning.

Clones may also become available that offer fine branching characteristics and therefore can be planted at low stockings without branch size becoming excessive and compromising wood quality (Mineham, 2009). However, tree stocking affects growth (Dean, 2007) and low initial stockings may not adequately control width of growth rings, so where planted at low initial stockings of 550 stems per hectare, care is required to ensure every tree grows well (Mineham, 2009). The current recommendation is to plant 600 clonal stems per hectare to give a greater "margin for error" (S. Rapley, pers. comm). Form issues and loss of leader still occurs with clonal material, caused by multiple factors such as wind gusts, cicadas and leafroller (S. Rapley, pers. comm). Only at very high stockings is the tree likely to grow back a single leader on its own and form pruning, although effective, is expensive (S. Rapley, pers. comm).

Clones have good consistency in their branching pattern and growth rates (Gray & Gray, 2012). Clonal stock is currently being selected for rapid growth, good stem form with good coloured heartwood, with low shrinkage and a basic density of greater than 320 kg/m^3 (Palmer & Rapley, 2012). Although more variable, seedlings can produce more rapid early growth rates (Gray & Gray, 2012). However, seedlings have higher levels of epicormic shoots and leaders are more likely to snap in the wind (Gray & Gray, 2012).

Although management of redwood is in its infancy and optimum regimes have yet to be developed, the target is to grow large pruned buttlogs and upper unpruned logs with live branches having diameters of no greater than 50 mm (Dean, 2007). Although there is a time delay between branches dying and the formation of bark-encased knots, thinning of redwoods should aim to minimise dead branches (Dean, 2007). Ideally, this can be achieved by maintaining a deep green crown through timely thinning and ensuring that if planted at a high initial stocking, this is not followed by delayed or late thinning (Silcock, 2008). However, in practice at a commercially acceptable final crop stocking, even when well managed, the first log above the pruned buttlog will tend to be the lowest quality log in the tree with abundant bark-encased knots in the sapwood (S. Rapley, pers. comm). Above this, the logs tend to have mostly green knots.

Because early pruning for a small defect core encourages production of epicormic shoots, management to maximise production of clear heartwood can be problematic. To overcome this and other management issues a mixed-species regime was developed for redwood plantations by Rob Webster (S. Rapley, pers. comm). Clonal redwood is planted at 400-500 stems per hectare with 400-500 Italian alders (Alnus cordata) as a companion crop. Italian alders are suitable because they are robust, don't mind weed competition, they grow on infertile ground, fix nitrogen and are a hardy tree that does not out-compete redwood (S. Rapley, pers. comm). The alders limit diameter growth of the redwoods and push them upwards, but without overtopping them. Alders were selected for companion planting because as coloniser species they tend to have vigorous early growth but then "run out of steam". If necessary the dominant alders are thinned out at 12 years of age to then encourage diameter growth in the redwoods (P. Silcock, pers. comm).

Trials have shown that redwoods are not out-competed by alders and after the first decade emerge as dominant (P. Silcock, pers. comm). By shading the pruned section of the redwood trunk, epicormic shoots are minimised (S. Rapley, pers. comm). Competition is not severe enough for the shade-tolerant redwood branches to senesce, but does limit their size. Redwood form is improved by the sheltering effect of the alder intercrop (P. Silcock, pers. comm). Pruning costs are lower because of less taper and smaller branches of lower frequency, therefore achieve greater height per pruning lift (S. Rapley, pers. comm), with 6.5 metres achieved in two lifts (P. Silcock, pers. comm). Furthermore, by constraining diameter growth during the establishment period, the core of lower density, less durable wood is minimised (P. Silcock, pers. comm). To date trials have shown that alders may not even need to be thinned out because natural senescence occurs as the redwoods dominate the site (P. Silcock, pers. comm). Alders also appear to be well enough adapted to hill country and their strong rooting habits would significantly decrease risk of erosion beyond what would be achieved with the low stocking rate for redwood clonal material, while sheltering the redwood crop during the critical establishment phase (P. Silcock, pers. comm).

Insect damage can devalue the timber, in particular native drywood termites (*Kalotermes brouni*) and a borer (Silcock, 2008). The species of borers and how management affects levels of damage does not appear to have been well studied in New Zealand. Entry of wood-damaging borers appears to be through dead wood that has begun to decay. Pruning out large double leaders can allow entry of borer, as can large pruning wounds where healing is slow, along with decaying dead branches (S. Rapley, pers. comm).

Redwood can be prone to double leaders (Purey-Cust, 2011), caused primarily by wind damage in early years (Gray & Gray, 2012). Where multiple leaders are formed in crop trees, form pruning is required to reduce these to a single leader (Gray & Gray, 2012). Clonal selections may produce less forking than seedlings (Gray & Gray, 2012), but clones are still susceptible to multiple leaders (S. Rapley, pers. comm).

Weed potential

Redwood has a very low potential for wilding spread because of low seed viability and the inability for the seed to travel more than a few metres from the parent tree (Wallwork & Rapley, 2009).

Timber

Redwood timber is low density, soft, dimensionally stable and easily worked (Webster, 2007). Redwood is also odour free, non-resinous and straight grained, with little shrinkage (Knowles & Miller, 1993). Heartwood colour varies from pinkish-red to brown and heartwood is naturally durable (Webster, 2007).

Redwood has a good reputation and used in the U.S. for exterior and interior joinery and weatherboards (Silcock, 2008) and because the heartwood is resistant to decay it is suitable for outdoor applications like exterior decking, fencing and garden structures (Webb, 2007). In New Zealand redwood complies with the building code as an acceptable solution for exterior cladding but not decking (NZS 3602:2003). Most redwood applications take advantage of its outdoor durability or attractive appearance (Webb, 2007). Redwood timber is considered to be too soft for framing and general uses (Cornell, 2007) although characteristic strength values have been determined for New Zealand material (NZFFA, 2015), potentially creating an opportunity for appearance structural applications using specific design, provided properties for fixings were determined (D. Gaunt, pers. comm).

New Zealand redwood has comparable properties with second-growth redwood from the U.S., which comprises over 95% of that market (Webster, 2007). However, New Zealand material can be slightly lower density, depending on genetics and growth rate (Brown, 2007) but has greater dimensional stability (Palmer & Rapley, 2012). Market value for redwood in California is significantly higher than for Douglas fir and radiata pine; and demand, being driven by sentiment, is high (Brown, 2007). There is also considerable demand for redwood in Asia (Webster, 2007) and opportunities also exist in the local New Zealand market (Brown, 2007). However, Tombleson (2007) suggested that sustained supply and demand is required for improved prices that justify growing the species, after finding that exceptional quality large pruned redwood logs fetched only equivalent to the average pruned radiata log price in the New Zealand market.

Small diameter logs (down to 20 cm diameter) may be sawn for utility uses (Dean, 2007). Sapwood material is commonly used for fencing in California and has proven to be adequate in New Zealand conditions (S. Rapley, pers. comm). Although the sapwood is susceptible to decay, this can be boron treated to resist decay, but not pressure-treated with water-borne preservatives (Knowles & Miller, 1993). Sapwood can also be treated with LOSP preservatives (S. Rapley, pers. comm). Thermal modification might offer opportunities for using sapwood material for applications like fencing where strength is not required.

The Californian market values clear heart grades and these attract a high market premium (Dean, 2007). Tight knot grades also attract a significant premium over timber with bark-encased knots, which potentially influences silvicultural management of redwood in New Zealand (Dean, 2007). Silcock (2009) found, however, that "the value decrease due to dead branches was not as marked as expected".

Sequoia, giant

Giant sequoia grows on free draining soils at altitudes of between 830 m and 2700 m in its natural range in North America, with little rainfall in the growing season and significant snowfall in winter (Knowles & Miller, 1993). It is very cold hardy (Knowles & Miller, 1993). Large specimens are found throughout New Zealand, demonstrating its wide climatic adaptability.

Giant sequoia is highly tolerant of gale force winds (Brown, 2007), tolerating much greater exposure than coast redwood (Knowles & Miller, 1993). Giant sequoia resists uprooting even in extreme winds such as during Canterbury windstorms in 1975 (Knowles & Miller, 1993) and again in 2013 (G. Fleming, pers. comm) both of which severely damaged other species including radiata pine, but with little or no damage to giant sequoia.

Siting

Trials were planted in New Zealand in the late 1970's near Gore, Geraldine and Hamner Springs in response to observations on its wind firmness. These have all grown well, with another at high elevation near Arthur's pass looking like it may have potential (Libby, n.d.). Brown (2007) suggested that giant sequoia should be more widely planted in the South Island.

Giant sequoia tends to grow best on slopes and where there is good soil drainage, with wet soils resulting in butt rot (Knowles & Miller, 1993). In New Zealand giant sequoia has established without shelter and in extremely dry conditions in Otago and can grow in much drier conditions than coast redwood (Knowles & Miller, 1993). It will grow on exposed barren ridge tops but prefers some intact topsoil (C. Low, pers. comm).

Management and silviculture

Giant sequoia, like coast redwood, responds well to being released from weed competition (Knowles & Miller, 1993). Growth can be slow for the first ten years or so, but then increases significantly (Knowles & Miller, 1993). Even on better sites growth is slow for five years, "but then height increases by 80-90 cm per year and can achieve 90 cm diameters at 25 years old" (C. Low, pers. comm).

Little is known about silviculture of giant sequoia, but like coast redwood, this should aim to minimise branch death and formation of black knots, while also minimising branch size (Knowles & Miller, 1993). Trees can become very large, with specimens in New Zealand achieving over 3m diameter at 120 years old and the species offers fast diameter growth even as it ages (Knowles & Miller, 1993). Giant sequoia has a more consistently good form than other conifer species (Knowles & Miller, 1993).

Only stumps from young trees sprout coppice growth (Libby, n.d.).

Rooting of cuttings becomes more difficult as parent trees age, however there is some evidence that clonal stock can be rejuvenated, which can then be hedged to produce large quantities of cutting material (Knowles & Miller, 1993). Seedlings are prone to botrytis disease in the nursery whereas cutting material isn't (Knowles & Miller, 1993).

Pests and diseases

Giant sequoia has been found to be healthy and relatively pest and disease free in New Zealand. Giant sequoia foliage is generally unpalatable to browsing and possum damage, less so than coast redwood, however the bark may be stripped by cattle and goats (Knowles & Miller, 1993).

Timber

The wood of plantation giant sequoia is similar to coast redwood (Libby, n.d.), but is slightly coarser in texture, darker in colour and possibly with slightly better mechanical properties (Knowles & Miller, 1993).

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