Chapter 7. Forestry

Long-term adaptation of productive forests in a changing climatic environment

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Abstract

The forestry sector has a different vulnerability profile to many other primary sectors given its slower biological response rate and long harvest cycle. Forestry is a large component of the New Zealand economy and its contribution is expected to significantly increase into the 2020's as 40% more wood becomes available for harvest. This chapter examines both direct and indirect impacts of climate change and reviews potential adaptation strategies. There is benefit to the sector, as productivity is projected to increase over the next 80 years under climate scenarios if increasing CO_2 concentrations and also given that there are no restrictions to growth from nutrient or precipitation limitations. However, risks increase under climate change for damage from fire, insects, disease and weeds. The adaptation options reviewed break down into managing the risk associated with the current investment in forests and infrastructure. Then, more strategic and transformational options are considered, that focus on the requirement for building resilience in future forests by examining the location, species, products and management, as well as regimes that are required for forestry within a potentially more variable and changing climate. The industry currently uses sophisticated adaptive risk management tools and practises managing risk, and careful consideration is given to how this approach can be adjusted to implement climate change adaptation over the coming wood harvest time frames. Forestry faces challenges compared to other primary sectors – such as, the uncertain impact of increasing CO_2 levels on forest productivity. To develop adaptation strategies for crops developed over the order of 30 years, forestry will be faced with the need to make large-scale investment decisions based on very uncertain long-term outcomes. Putting these adaptation approaches into a financial risk management model would be a logical next stage for the sector as it considers how it will develop and implement any adaptation strategies.

Contents

1 Introduction

This chapter reviews the risks, and outlines adaptation strategies, associated with climate change impacts on New Zealand's plantation forest resource. New Zealand's indigenous forests are not part of the productive sector, hence the projected climate impacts on natural forests are not considered in this chapter.

Forestry provides about 3% of New Zealand GDP (Dec 2011), and has annual export earnings of NZ$4.26 billion (projected June 2012, MAF 2011b) – making it New Zealand's third largest merchandise export earner. The sector employs 31,800 people (1.4% of the national workforce) (WoodCo 2012).

Capital investments in the sector are estimated to be worth NZ$20.9 billion (Dec 2011), made up of NZ$15 billion investment in planted forests, NZ$5 billon in wood processing, and NZ$900 million in logging and transport infrastructure (WoodCo 2012).

The importance of the sector to the economy will increase, due to a projected 40% (10 million m^3) increase in wood availability from the existing planted estate into the 2020's. The export earnings are projected to increase from between NZ$5.9 billion to NZ$12 billion by 2022 (WoodCo 2012). Forestry is a strong and profitable sector that will continue to provide significant economic benefits to New Zealand.

New Zealand forest is made up of large sustainable monoculture plantations of radiata pine (1.74M ha) and Douglas fir; with small areas of other species such as eucalyptus and c. 1000 ha native forest plantations (Bergin D, Scion, 2011, pers. comm.). The radiata pine resource has a current standing volume of 479.7M m^3 (Apr 2011; MAF 2011a) see Figures 7.1 and 7.2, which will increase significantly as the average resource age increases.

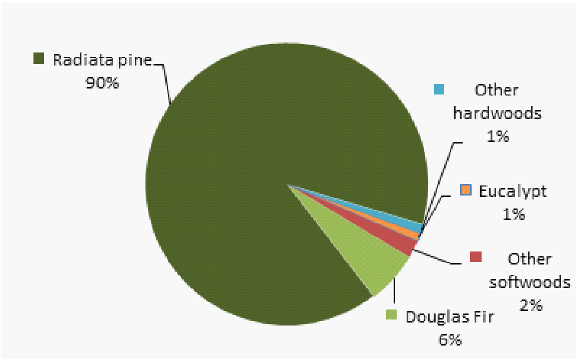

Figure 7.1. Forestry species distribution in New Zealand by percentage of the plantation estate area (Source MAF 2011a).

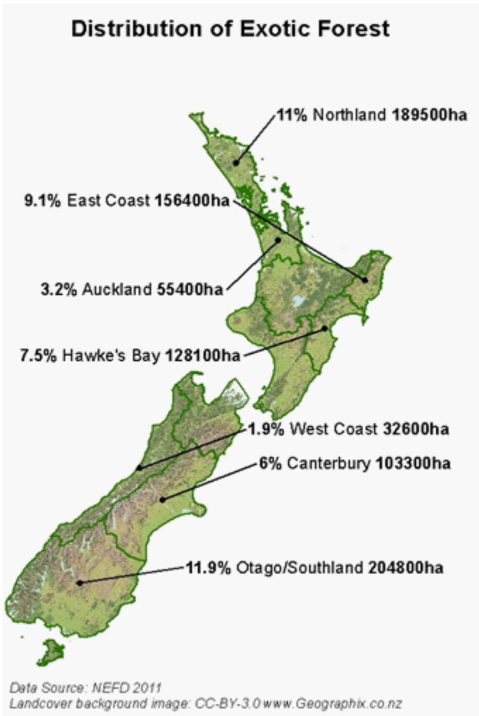

Figure 7.2. Distribution of exotic forest in New Zealand by region (MAF 2011a).

Adaptation to climate change can be defined as the: 'adjustment in natural or human systems in response to actual or anticipated climate stimuli or their effects which moderates harm or exploits beneficial opportunities' (IPCC 2007).

Adaptation to climate change identifies mechanisms that allow the forest manager to response to both the risks to production and the opportunities that arise from climate change. Managing for climate change is particularly important for forestry as it takes years to realise commercial gain from a crop. Hence, managing for climate change or adapting for climate change largely focuses on management and adapting to changes in risk profiles especially for the NZ$15 billion of existing plantation forest. To date, most research has been on understanding the potential impacts and risk of climate change and modelling changes in productivity due to climate change.

The impacts of a changing and more variable climate on forests are varied, as trees are typically long-lived and well adapted to normal climate variations. Negative impacts can increase, however, when climatic changes push forested ecosystems outside their natural range of climate variability and beyond the ecosystem's ability to adapt.

Ecosystem responses to extreme shifts are complex, have multiple primary and secondary interactions, which can be additive, multiplicative and non-linear, or partially cancelling. There can be tipping points from which the system cannot return even if external driving forces return to their pre-disturbance values (Parks & Bernier 2010). Impacts can be mitigated to some extent by reducing greenhouse gas (GHG) emissions or adapted to by modifying management practices that build resilience or reduce vulnerability. However, adaptation only moderates vulnerability to climate change (Spittlehouse & Stewart 2003).

Climate change will affect plantation forests with direct impacts on productivity from changing temperature, rainfall, wind and CO_2 concentration; and indirect impacts of changes on the forest ecosystem such as on weeds, pests and diseases (Watt et al. 2008).

While the drivers of climate change are global in origin, many of the impacts and responses are local and are defined by the ***site specific*** interactions of climate, environment, forest ecosystem and societal capacity and needs (Parks 2010).

The chapter reviews the climatic growing condition of radiata pine in New Zealand, then summarises the direct impacts of changes in temperature, atmospheric CO_2 concentration, and water availability on plant productivity. It also reviews modelled projections of different climate change scenarios on radiata pine productivity. The indirect impacts on forest productivity caused by the impacts of climate change on other forest biological populations and physical processes are then reviewed.

Most of the literature is focussed on the generic C3[1] plants and the radiata pine-specific information is sourced from limited New Zealand and Australian research. However, the productivity modelling work and some pest modelling uses New Zealand data and climate scenarios. There are limited research results on the impacts of CO_2 enrichment in the New Zealand context through FACE experiments; and limited field research exists on the impacts to insects, weeds, pests and fire on productivity even under current climate conditions.

Potential adaptation strategies are reviewed in Section 2. Published literature on this topic is scarce, with few specific strategies reported that have any adaptation research undertaken for plantation forests. Research is also further limited for radiata pine or Douglas fir plantation forests.

The final section of this chapter (Section 6) discusses the implications of the adaptation options listed and identifies where the knowledge gaps lie.

2 Overview of growing conditions for radiata pine

This section summarises the climate envelope of growing conditions for radiata pine.

2.1 Growing conditions for radiata populations

Radiata pine, or Monterey pine (***Pinus radiata***) is an exotic tree species introduced to New Zealand. It is

[1]Photosynthetic processes in plants are either C_3, C_4 or CAM. Productive forest species and most weeds species are C3 photosynthetic plants – where photosynthesis occurs in the leaves and the Rubisco enzyme is involved in CO_2 uptake.

indigenous to North America at Ano Nuevo, Monterey, and Cambria; and at two island populations in Guadalupe Island and Cedros Island (Shelbourne et al. 1979).

Successful establishment of plantations require a minimum annual rainfall of 600–750 mm (FCV 1982; Grey & Taylor 1993). Where there are heavy summer droughts or high soil moisture deficits, new plantings face the risk of failure (Lavery 1986). Lavery (1986) states that climates with high humidities in the warmer seasons are hazardous to the long-term viability of Radiata pine. In such conditions, the species is susceptible to various pathogens such as ***Dothistroma septosporum*** (causing needle-blight) and ***Cyclaneusma minus*** (causing needle-cast).

Radiata pine has a limited tolerance to frosts. Menzies & Chavasse (1982) using the minimum acceptable survival of 80% of planted seedlings as a frost tolerance threshold, gave a frost tolerance of - 6°C in January and February dropping to –13°C for June to August, rising to - 6°C by November and December.

Most New Zealand radiata pine does not experience a dormant period. Diameter growth is more or less continuous throughout the year (Jackson & Gifford 1974a). Hunter & Gibson (1984) suggested that the optimal mean annual temperature for productivity is 12°C, and Kirschbaum & Watt (2011) suggested a slightly higher optimal mean annual temperature of about 13°C. Nicholls & Wright (1976) suggest that diameter growth drops when mean annual temperate falls below 9°C. Jackson & Gifford (1974a, b) used the optimal night time temperature of 5°C and an optimal daytime temperature of 20°C (Hellmers & Rook 1973), as variables in a model of site productivity. Deviations in either direction had negative effects on productivity. Kirschbaum & Watt (2011) recently modelled the growth of radiata pine in New Zealand and concluded that most stands are currently grown at sub-optimal temperatures, with only stands in the warmest regions of the country experiencing optimal or slightly supra-optimal temperatures.

Productivity gains from rainfall are dependent on soil depth and soil drainage. The salient features of the interaction between rainfall and soil properties are:

- at any given level of mean annual precipitation, productivity increases as effective soil depth increases
- the deepest and most freely draining soils that are the most productive and on these soils productivity increases almost linearly with rainfall
- on the shallowest soils there is a point where increased rainfall leads to a drop in productivity (Jackson 1974 a, b).

Jackson & Gifford (1974b), also suggest that soil moisture holding capacity is critical. Waterlogging can be an overriding growth factor (Poutsma 1960).

Changing climatic conditions increases the risk of higher disease severity for some diseases. Gadgil (1984) demonstrated that temperatures over 10°C and continuous rainfall for over 5 hours /day are optimal for Cyclaneusma needle-cast infection, but in areas where there is low autumn-winter rainfall, Cyclaneusma should not be a problem.

Dothistroma is a fungus which infects trees and causes a disease (needle-blight) that eventually kills needles by reducing leaf area. Its distribution is related to temperature and moisture and is found in the North Island south of Auckland (Kershaw et al. 1988; Bulman et al. 2004).

Radiata pine shows a tolerance to a wide range of soils (Hinds & Reid 1957), with a minimum soil depth of 0.9–1.2m (Scott 1960). Trees grown on some soil types exhibit symptoms of nutrient deficiency, such as the phosphorus deficiency observed on clay soils, and the nitrogen deficiency seen on sandy and raw soils. Jackson & Gifford (1974 a, b) used the amount of nitrogen and phosphorus in the 0–7.5 cm soil layer as significant parameters in their model of productivity.

Exposure to wind can limit productivity through lower tree height and reduced diameter growth (van Laar 1967). Severe wind damage has been reported at wind speeds > 50 km/hr (Somerville 1980). The risk of damage increases after thinning and for stands in proximity to harvested areas, and is also related to topography (Knowles & Paton 1989). Wind throw is common on shallow or saturated soils (Versfeld 1980), and damage from breakage will predominate over damage from wind throw for deep rooting soils (Hocking 1947). Watt et al. (2010) reported yield reductions of about 20% between sites experiencing highest and lowest annual average wind speeds.

Elevation has effects on tree growth, primarily due to its modification of climatic variables and effects on wood properties, where wood density changes with elevation and latitude (Cown & McConchie 1983). Lavery (1986) provides the following two rules of thumb: (i) density decreases with increasing altitude, at a rate of 7 kg/m^3 for each 100m rise in elevation; (ii) density decreases with increasing latitude at a rate of 6.5 kg/m^3 per degree of latitude. The wood density model (Beets et al. 2007) related these changes in density to temperature and found that wood density can be affected by tree nutrition, stand density and stand age.

Stand and climatic variables affect the height to diameter relationship in trees; higher temperatures and stand densities (but lower fertility or topographic exposure) favour relatively taller and thinner trees (Watt & Kirschbaum 2011).

Reports from the published literature and from commissioned technical or governmental reports (from New Zealand and overseas) have been used to identify potential impacts and risks to radiata pine productivity. Table 7.1 provides a knowledge summary from this review and details whether the knowledge is derived from New Zealand or overseas studies.

Table 7.1. Impact knowledge summary based on published scientific and available industry literature.

Climate driver	***Impact***	***New Zealand experience***	***Anticipated based on international experience, literature, or theory***
Increasing Temperature	Direct		
	Higher tree productivity (higher photosynthesis)/ Increased growth rate	Modelled responses Kirschbaum et al. (2011); Watt et al. (2008)	
	Increasing wood density	Beets et al. (2007)	
	Indirect		
	Potential productivity loss due to competition from increased weed productivity		Impact can be inferred from studies. No direct evidence available (see Section 4.2)
	Productivity decrease due to increased insect/disease range affecting more forest	Douglas Fir may have spatial range reduced (Watt 2011)	Strong supporting evidence internationally. Impact can be inferred from studies (see Section 4.1)
	Productivity decrease due to increased insect lifespan		Strong theoretical basis (see Section 4.1)
	Insect damage affecting productivity on tree with more insect generations		Strong basis (see Section 4.1)
	Increased fire risk with drier fuel	Pearce et al. (2011)	Strong supporting evidence (see Section 4.5)
	Increased fecundity and aggressiveness in some necrotrophic and biotrophic fungi		Strong theoretical basis. Pinkard et al. (2010)
	Direct		
	Increased growth in sites not nutrient-limited	Well projected responses	
	Increase in water use efficiency for sites with water limitations	Modelled responses Kirschbaum et al. (2011); Watt et al. (2008) (see Section 3.3)	Strong publication record (see Section 3.3)
Increasing CO_2	Decrease in wood density	Some research (see Section 4.4)	

	Decrease in microfibril angle	Some research (see Section 4.4)	
	Direct		
	Increased productivity in some water-limited environments with increased water use efficiency	Modelled responses Kirschbaum et al. (2010); Watt et al. (2008) (see Section 3.3)	Strong theoretical basis (see Section 3.3)
	Indirect		
	Increasing development and reproductive rates in some insects guilds		Strong theoretical basis (see Section 4.1)
	Reduced growth rates of some insects due to lower nutrient concentrations		Theoretical basis (see Section 4.1)
Decreasing rainfall	Direct		
	Fire risk increases	Pearce (2011)	Strong theoretical basis (see Section 3.3)
	Potentially greater weed composition as lower rainfall prevents plantation species from forming a close canopy so that weeds continue to persist and compete for resources	Strong theoretical basis	
Increasing frequency of extreme storm events	Erosion	On-going research	
	Infrastructure damage	Practical evidence	
	Increased fire ignition risk from lightening		Theoretical basis (see Section 4.5)
	Toppling and wind throw	Moore et al. (2011)	

3 Direct climate impacts on forest productivity

Climate change impacts from increasing temperature, increasing CO_2 concentrations, and changes in precipitation will change tree photosynthetic[2] and respiration[3] rates which may increase or decrease whole tree productivity. Hennessy et al. (2007) concluded that elevated CO_2 will generally improve productivity of exotic softwoods but the amount of change in productivity is affected by the degree of climate change and the impacts which that has on tree physiology. Productivity will also be affected by the impacts on ecosystems processes such as nutrient cycling; and by the interaction of site factors and forest management (Battaglia et al. 2009).

National projections for New Zealand (Ministry for Environment 2008; Chapter 2 Section 4.2) show warming of around 1.1°C by mid-century and 2.1°C for the end of the century under the A1B emissions scenario. There are large seasonal and regional differences in rainfall change. In Chapter 2 maps and tables are provided which detail these changes (Figures 2.13-2.17; Table 2.2). In short, there are fewer cold temperatures and frosts, and more high temperature episodes. The projections are the averaged results from 12 climate change models for the mid-range emissions scenario (A1B), using statistical downscaling. They represent a central value of a range of models and emission scenarios. These statistical downscaled projections have been used to model changes in radiata pine productivity (Section 3.4). New projections using alternative downscaling methods have also been used (Box 7.1).

[2]Photosynthesis: The bonding of CO_2 and water to make sugar and oxygen. The sugar is used as stored energy within the plant.
[3]Respiration: The energy in sugar is released.

Box 7.1. A note on projections.

Two different projections of future climate (based on different modelling methods) are used in this chapter.

Most of the research reported in this chapter and in the literature in general have used the projections from statistically downscaled climate models.

Emerging climate projections using a regional climate model have been developed for three scenarios (A1B, A2, B1), (see Chapter 2, Section 4.3.3.2) for one climate change model (HadAM3P). The A2 and B1 emissions profiles provide 'high' and 'low' Primary Sector Adaptation Scenarios respectively (Chapter 2, Section 4.3.3). The projected annual temperature and precipitation change between 1980–1999 and 2030–2049 (midpoint reference year 2040) in Chapter 2 (Figures 2.26 and 2.27), along with a national time series from 1970-2100 (Figure 2.28).

This data have be used to develop productivity projections of radiata pine using CenW (Kirschbaum 2012, unpublished data) and the preliminary results are discussed in Boxes 7.2 and 7.3. These emerging projections provide a more physically plausible climate projection at higher spatial resolution, albeit for only one global model, than the statistically downscaled projections which quantify the full range of potential outcomes. Both sets need to be considered to fully anticipate possible productivity impacts for New Zealand

3.1 Temperature impacts on forest productivity

Most biological and chemical processes in forest ecosystems are affected by temperature, and the impacts on tree productivity are complex; involving interdependent effects on photosynthesis, respiration, transpiration, nutrition, and plant development (Lambers et al. 2008). Photosynthetic rate is generally strongly affected by temperature. Plants are not expected to experience problems from a temperature increase alone, as the projected rise in temperature is too small to have a detrimental impact. This is because plants can tolerant temperatures higher than current temperatures and can acclimatise to a new temperature environment, although beyond a certain temperature, growth and survival will decrease (Way & Oren 2010). This may (or may not) be related to water stress (van Mantgem & Stephenson 2007; Piao et al. 2008). Any responsiveness to increasing temperature is principally driven by the lengthening of the growing season (Lieth 1973; Kirschbaum 2004; Pinkard et al. 2010). However, extreme and rapid temperature increases could be detrimental, resulting in extensive tissue damage, protein denaturation and mortality (Ögren & Evans 1992). Way & Oren (2010) concluded that temperature rise will enhance tree growth for deciduous species more than for conifer species and any increase in growth will vary between species.

3.2 Atmospheric CO_2 effects on generic tree productivity

The impact of elevated CO_2 concentrations on trees is complex with well characterised effects of elevated CO_2 concentrations on photosynthesis, suggesting the potential for substantial growth responses. (Farquhar & von Caemmerer 1982; Curtis 1996; Eamus & Ceulemans 2001; Ainsworth & Long 2005; Long et al. 2006; Abrams 2011). Representative results include:

- Turnbull et al. (1998) and Tissue et al. (2001) found that photosynthesis increased by between 30% and 50% for a doubling of CO_2 concentration under conditions without water or nutrient limitations.
- Ainsworth & Long (2005), in their meta-analysis of existing FACE sites, reported an on-going stimulation of photosynthetic carbon gain by 29%, which led to a 28% increase in biomass increment.
- Norby et al's. (2005) summary of FACE experiments found that for seven different species studied in four different experiments, the growth enhancement from elevated CO_2 concentration was a consistent 23%. As the summary covered species and growing conditions for which growth rates varied nearly five-fold, it suggested that the response was not dependent on the inherent growth rate of plants and refers to conditions where the response was largely controlled by the impact of CO_2 concentration on direct plant physiological processes. All seven sites had adequate access to sufficient water, and nutrient limitations were apparently largely absent from these sites.

There is debate around the magnitude of growth responses to elevated CO_2 concentrations (Nowak et al. 2004; Körner et al. 2007), reducing the certainty of projected responses of productivity arising from increases in future CO_2 concentrations. Plants regulate various metabolic processes for an overall balance, so if a resource (e.g., carbon) becomes more readily available, extra growth will only occur if plants can utilise it. When a plant's capacity to utilise carbon is limited ('sink limited'), any increase in photosynthesis cannot be sustained and will be curtailed through feedback processes called 'downward acclimation'. In the field[4], responses to increasing CO_2 concentrations will be limited if increased photosynthetic carbon gain cannot be matched by nutrient supply. Under these circumstances, lower foliar nutrient concentrations are likely to reduce inherent photosynthetic rates (e.g., Rastetter et al. 1997; Kirschbaum et al. 1998; Nowak et al. 2004; Norby et al. 2010).

Carbon allocation under elevated CO_2 conditions may change within the tree. Under these conditions, several studies have found relatively greater allocation to needles and fine roots (Norby et al. 2002; Hyvonen et al. 2007); while other studies found an increase in root growth (Matamala & Schlesinger 2000; Pregitzer et al. 2000; Pritchard et al. 2001). It is unclear if there will be a change in carbon allocation (i.e., change in the shoot:root ratio) with increased CO_2 across species (Medlyn et al. 2001a; Karnosky, 2003).

There is little evidence of a net increase of nutrient availability from nutrient cycling under elevated CO_2 conditions (Millard et al. 2007).

3.2.1 Interaction of temperature and CO_2

The sensitivity of photosynthesis to CO_2 concentration increases with increasing temperature (Kirschbaum 2004), with increases in the photosynthetic and photorespiration rates (Sage & Kubien 2007). Plant growth will increase with elevated CO_2 concentration and also with higher temperatures, with little or no growth at low temperatures (Kimball 1983). However, Norby & Liu (2004) warn that it will be difficult to make conclusions about how this experimental observation will affect production, because of the many other factors influenced by temperature – including the optimum temperature for a particular species' growth. Temperature is projected to increase concurrently with CO_2 concentrations. However, there are few studies that have examined this interaction on tree growth (Way & Oren 2010). Until further research is performed, it is unclear if any increase in productivity is due primarily to elevated CO_2, temperature, or both.

3.3 Effects of precipitation on generic tree productivity

Water limitation is a major factor that directly impacts plant growth (Schulze et al. 1987), with increased mortality, and indirectly with increased susceptibility to, and damage from, pests and fire (Pinkard et al. 2010). Plant responses to reduced water availability are multifactorial (Wullschleger et al. 2002) and based on soil water availability, and impacts of temperature and CO_2 levels on water exchange with trees. Plant water management is controlled by stomatal response to changes in atmospheric CO_2 concentrations.

Plants acquire CO_2 and emit water vapour via their stomata (the microscopic pores on leaves). To maximise growth, plants need stomata to open as much as possible to assimilate CO_2 for photosynthesis, but this also allows water vapour to be emitted (effectively wasting it). Plants optimise the trade-off between CO_2 assimilation and water transpiration (Cowan & Farquhar 1997) by closing and opening stomata, resulting in changes to stomatal conductance. Lower stomatal conductance limits water loss (transpiration) more than it limits CO_2 assimilation (Farquhar & Sharkey 1982); but it does reduce CO_2 assimilation and, consequently, photosynthesis (Lambers et al. 2008). Stomatal conductance is inversely related to atmospheric CO_2 concentrations, though different plant groups have different responses at increased CO_2 levels, with conifers being significantly less responsive than angiosperms especially at CO_2 concentrations above 380 ppm. They found that as conifers' stomatal conductance did not decline much after CO_2 concentrations reached 380 ppm, this provided an increase in CO_2 assimilation at 600 ppm – thereby providing increased productivity at higher CO_2 concentration levels. They hypothesised that conifers most probably evolved under CO_2 concentrations substantially higher that 600 ppm (Brodribb et al. 2009). Morison (1988, Allen (1990) and Urban (2003) compiled a range of observations from the literature and showed that stomatal conductance's across a range of species were reduced by about 40% when CO_2 concentration was doubled. However, stomatal conductance in woody species was generally observed to be less sensitive to CO_2 concentration, with Curtis & Wang (1998) meta analysis reporting a non-significant stomatal conductance reduction by just 11%. Curtis & Want (1998) however reported numerous studies of having negative, non significant or positive effects of high CO_2 concentrations in stomatal conductance, whereas Medlyn et al. (2001a, b) reported 21% reduction in stomatal conductance across a range of studies. Medlyn et al. (2001a, b) also reported that the response appeared to be weaker in older rather than younger trees and weaker for conifers than deciduous trees.

[4]Downward acclimation has been observed mainly in pot trials (Arp 1991), and may be largely related to experimental artifacts related to growth in small pots where the plants' inability to grow larger induces a sink limitation (Kirschbaum 2011). Downward acclimation is observed less frequently in large pots or field trials.

Water use efficiency (WUE) is the ratio of CO_2 assimilated to water lost and is strongly affected by stomatal conductance (Wang et al. 2012). Increases of up to 40% were observed in conifers (at 600 ppm). WUE improvement means that under enhanced CO_2 conditions, less water is lost and photosynthesis can proceed for longer without water stress developing. This provides continued growth when there are reductions in precipitation. Productivity gains from improved WUE are substantially greater than gains from enhanced CO_2 concentrations alone. Therefore, the greatest relative gains are likely on water-limited sites with adequate nutrition, since feedback inhibition will be minimised, and WUE (rather than direct CO_2 responses of photosynthesis) will be of greatest importance (Kirschbaum 1999b; Körner et al. 2007).

While the arguments in support of increasing CO_2 responsiveness with decreasing precipitation are compelling, experimental support for this pattern is less strong. Increasing WUE has generally been observed in small-scale studies of both woody and herbaceous species (Eamus 1991). Nowak et al. (2004) summarised results from existing FACE sites. When results for each site were averaged, they conformed to the expected pattern of increasing growth response with decreasing rainfall. However, the same data provide a different pattern if years and sites were analysed separately. Results under the more extreme desert conditions showed that there was greater CO_2 enhancement of above ground growth at moderate precipitation levels than at the lowest precipitation levels.

The reasons for these inconsistent patterns are not clear, but it casts some doubt on the expected greater growth enhancements under water-limited conditions. Wang et al. (2012), in water-limited sites in China, found growth reduction even with increased WUE – which is consistent with other results (see Wang et al.2012, p.21). Penũelas et al. (2011) found similar results when reviewing WUE and growth, with only 50% of sites showing growth gains, the remainder showing either no change or growth losses. Wang et al. (2012) also noted that the increase in WUE is probably drought-influenced, and driven by a large decrease in water loss through stomatal closure (as the WUE denominator), rather than by an increase in CO_2 assimilation.

Within water-stressed sites, increased temperatures could produce high evapotranspiration rates exacerbating any drought stress (Wang et al. 2012). Sustained increases in air temperature can increase transpiration (Turnbull et al. 2001) which may decrease growth.

In New Zealand, it is likely that stomatal conductance will be significantly reduced in response to increasing CO_2 concentrations: especially later in the 21st century, and more so under the A2 than B1 scenarios, because of the higher CO_2 concentration of the A2 scenario. That reduction in stomatal conductance is likely to be less pronounced if photosynthesis increases in response to increasing CO_2 concentrations. Decreasing stomatal conductance will reduce transpiration rate, but any increase in temperature, both as a direct factor and indirectly by increasing the vapour pressure deficit of the air, will increase transpiration rates from canopies. The direct physical effects from increasing temperature, together with the plant physiological effect of decreasing stomatal conductance, will partly cancel each other out. Overall, the best quantitative assessment of the net effect of stomatal closure and a relatively slight temperature increase, is for a slight decrease in transpiration rate by 2040 and a somewhat more substantial decrease by 2090. These reductions in transpiration rate will be greater if photosynthetic rates remains unresponsive to CO_2 concentration, but lesser if there are gains in photosynthesis (Kirschbaum 2004).

For New Zealand, simulations that included increasing CO_2 concentration led to higher modelled productivity – even for regions where moderate reductions in rainfall are expected, and where evaporative demand could increase with higher temperatures (Kirschbaum et al. 2012).

Growth is reduced on sites with precipitation shortfalls (e.g., Arneth et al. 1998a,b; McMurtrie et al. 1990; Richardson et al. 2002), which can be intensified on sites with low water holding capacity. This research is consistent with CenW simulations that showed productivity increased with up to approximately 2000mm of precipitation, and productivity reduced at supra-optimal precipitation (Kirschbaum & Watt 2011).

Water balance is affected by the combined changes in water inflows and outflows, the water-holding capacity of the soil, and by evapotranspiration (which is generally the most substantial component of water loss from the system). Any changes in the annual distribution of rainfall are likely to affect soil water availability at different times of the year.

Within New Zealand, the low to moderate changes in annual mean rainfall expected under climate change are likely to have little impact on water balances (Chapter 2, Section 3.2.2 provides a detailed analysis of changes to rainfall under changed climate conditions). Figure 2.14 shows the projected mean annual precipitation change for 2040 and 2090 for the A1B (mid emissions scenario), Figure 2.15 provides the projected mean seasonal precipitation changes.

Under New Zealand conditions, with relatively small anticipated increases in temperature, temperature-driven increases in evapotranspiration rates are likely to be more than offset by stomatal closure in response to increasing CO_2 concentrations. This will lead to an overall reduction in evapotranspiration that is greater than anticipated reductions in precipitation. Hence, even regions that are currently water-limited could see slight improvements in their water status in future.

3.3.1 Drought

Drought is likely to lead to reduced plant growth and altered plant recruitment. The drought stress of trees will also predispose forests to infestation by insect herbivores and fungal diseases (Kolstrom et al. 2011).

There are a variety of physiological processes in plants that respond to plant water potentials (Hsiao 1973; Ditmarová et al. 2010), so that the severity of a drought will influence the physiological response (Ryan 2011). The effects of drought are relative: tree species from wetter biomes will be more susceptible to reductions in precipitation than species from drier biomes that can survive low soil water (Ryan 2011).

Figure 2.15 shows the projected seasonal precipitation changes between 1980–1999 and 2030–2049 and between 1980–1999 and 2080–2099. A consistent signal from global climate model projections is for an increase in the westerly wind circulation over New Zealand, especially in winter and spring; with a corresponding projected increase in annual mean precipitation in western regions of New Zealand, and a decrease in rainfall in the east of the country.

3.3.2 Future forest productivity under expected climatic changes

Empirical growth models developed using datasets from historical and current growth conditions are unsuitable for predicting growth under climatic conditions that are outside the bounds of the models. Process models are more suitable tools for future projections of productivity, as they incorporate processes, interactions and feedbacks that are affected by climatic variables of interest such as CO_2 concentration, precipitation and carbon sequestration (Kirschbaum et al. 2012). These models can be used with greater confidence to estimate and undertake sensitivity analyses on how future conditions may influence productivity.

Kirschbaum et al. (2012) used CenW model (v 4.0; Kirschbaum 1999a) to model productivity into the future for 2040 and 2090 under different climate assumptions. The climate change data was derived from 12 climate change models, statistically downscaled to 0.05 degrees and forced by three emissions scenarios: B1 - low, A1B – mid range, and A2 – high). CenW was run under both constant 1990 CO_2 concentration and the specific CO_2 concentrations corresponding to those expected by each of the emission scenarios.

3.3.3 Climate change simulations with constant CO_2 concentrations

Simulations with constant CO_2 concentrations showed adverse effects of climate change on wood productivity in northern and low altitude regions within the North Island under most scenarios (Figure 7.3). Reductions in wood productivity were especially marked for the high-emission A2 scenario and were more pronounced for projections to 2090 than for 2040 (Figure 7.3). In contrast, wood productivity is likely to increase in the cooler parts of the country, including most of the South Island and in higher altitude regions of the North Island (Figure 7.3).

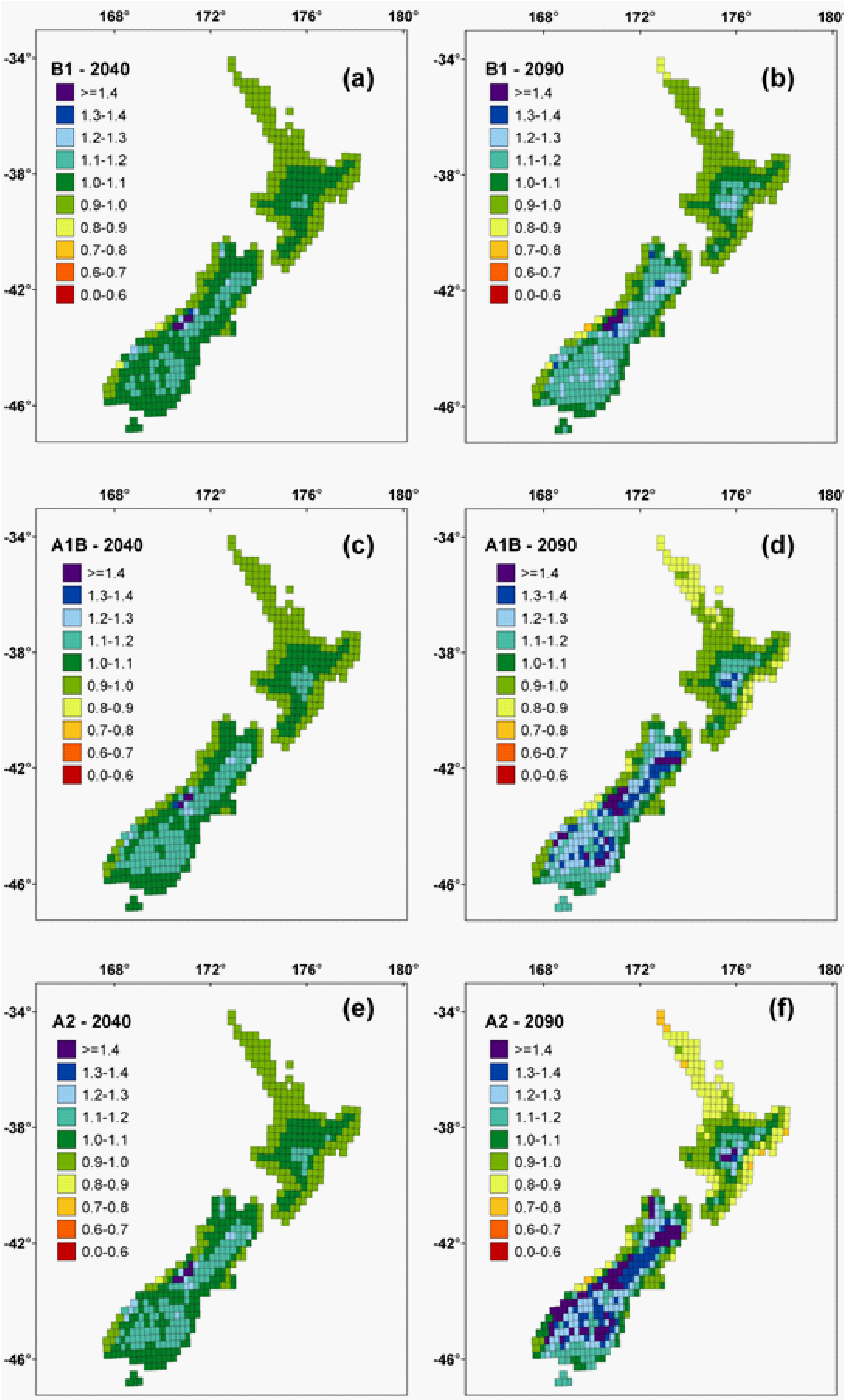

Figure 7.3. Climate change impacts on future wood productivity to 2040 (a, c, e) and 2090 (b, d, f) under the B1 (a, b), A1B (c, d) and A2 (e, f) emission scenarios. These climate change simulations used constant present-day CO_2. Results are expressed as the ratio of future wood productivity over current-day productivity. Data show the average productivity response under simulations run separately under the climatic projections of the 12 different GCMs.

Box 7.2. Forest productivity under the Primary Sector Adaptation Scenarios.

Climate change research has traditionally used GCM runs of daily weather patterns, averaged the results for some years or decades under current and future climatic conditions, and then reported the difference in those averaged conditions (e.g., temperature increase by 3°C from 1990 to 2090). The daily weather shows considerable variability over periods of years to decades, and the averaging is done to extract a climate change signal rather than being overly influenced by the coincidence of the weather in a particular period being abnormally warm or cold.

The average climate change is then typically added to observed current day weather patterns to generate a realistic future pattern of daily weather. This has the advantage that the weather patterns, such as seasonality and recurrence of important events (e.g., as extreme rainfall, droughts or high temperatures) are retained in the future-climate simulations. However, it implicitly assumes that the weather pattern itself will not change into the future.

However, weather patterns may change. For example, the average amount of precipitation at one site may not change, but it may be distributed more or less evenly, leading to more or less drought and flooding events. These types of changes would be missed in the traditional approach to climate change studies.

The alternative approach is to directly use the output of daily weather generated by a regional climate model (RCM; see Chapter 2, Section 4.3.2). The obvious strength of this approach is that it captures all aspects of climate change. However, the weaknesses are that it is subject to both the randomness of the weather (even apart from climate change); and that weather sequences are not readily available for more than one climate model – so that any biases or peculiarities of the particular climate model also unduly influence the overall weather sequences to be used. The Primary Sector Adaptation Scenarios (PSAS) used here are derived from this approach, but with some additional downscaling to correct biases and provide a site specific projection (Chapter 2, Section 4.3.3.2) With this new approach to downscaling, there is also an opportunity to produce a finer spatial resolution assessment of forest productivity impact on climate change than with the previous approach.

This new approach was, therefore, adopted in a new study as part of the present work. The preliminary findings are briefly described in this Box and in Box 7.3.

The new simulations show a similar general pattern to the older simulations, but with more pronounced patterns of change (Figure 7.4). With constant CO_2 concentrations, positive productivity changes were found for the cool regions in the South Island and the central plateau of the North Island; with negative changes for the warmer north and the drier east coasts of both islands and for the wet West Coast (where the current excess precipitation is expected to further increase).

This general pattern becomes more pronounced under the PSAS, with more significant productivity reductions in the north of the country, across the drier east coasts and on the already excessively wet West Coast of the South Island. These changes reflect both a redistribution of rainfall under the PSAS, with more rainfall in the west and less in the east, and more pronounced temperature increases. Increased temperature leads to greater transpirational water losses from plant canopies and thus intensifies water limitations in both the north and the east of the country.

With increasing CO_2 concentration also factored in (Figure 7.5), productivity changes became more positive compared to the simulations with constant CO_2; but the overall less favourable outlook compared to the older scenarios remained. Significant positive effects were modelled for most of the central plateau of the North Island and most of the South Island except for the West Coast. The negative growth expectations for the far north, and the east coasts of both islands were largely ameliorated, with an expectation of little change.

These differences in predicted responses fall within the range predicted by the larger number of climate models used in the previous work. (cf. Fig. 7.3). This previous work (Kirschbaum et al. 2012) reported the average response from runs based on the climatic output from 12 different GCMs, with the reported averages covering a range of responses from simulations of individual GCMs. The PSAS used for generating the newer runs produced stronger climate change responses (e.g. greater temperature increases) than the average of the previously used models. Consequently, simulated productivity effects were more pronounced. Radiata pine is currently grown under slightly sub-optimal temperatures in most of New Zealand (Kirschbaum & Watt 2011), so that slight climate change would not be expected to have pronounced effects on productivity. However, with more pronounced temperature increases, stands would be progressively pushed into supra-optimal temperature regions, with progressively more negative consequences as the degree of climate change increases.

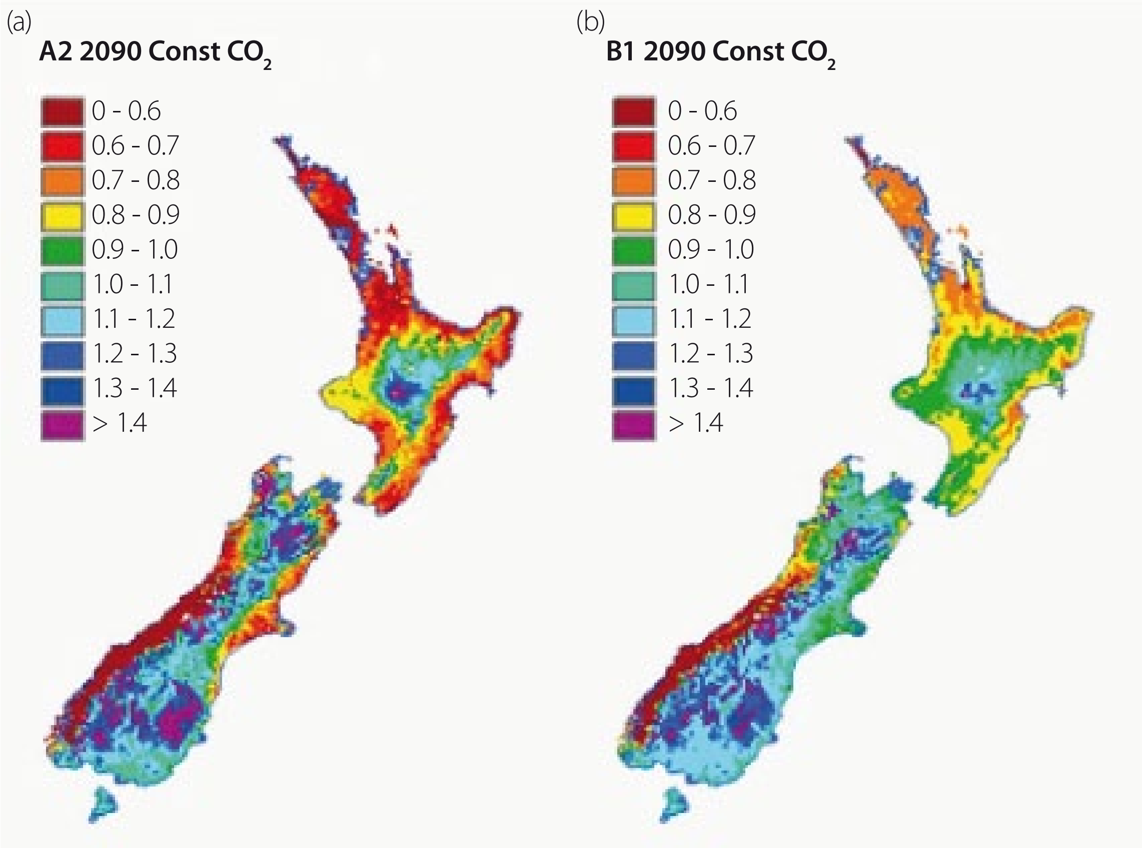

Figure 7.4. Relative change in volume productivity for 2090 compared to 1990 under constant CO_2 concentrations. (a) A2 – High emission scenario. (b) B1 – Low emission scenario.

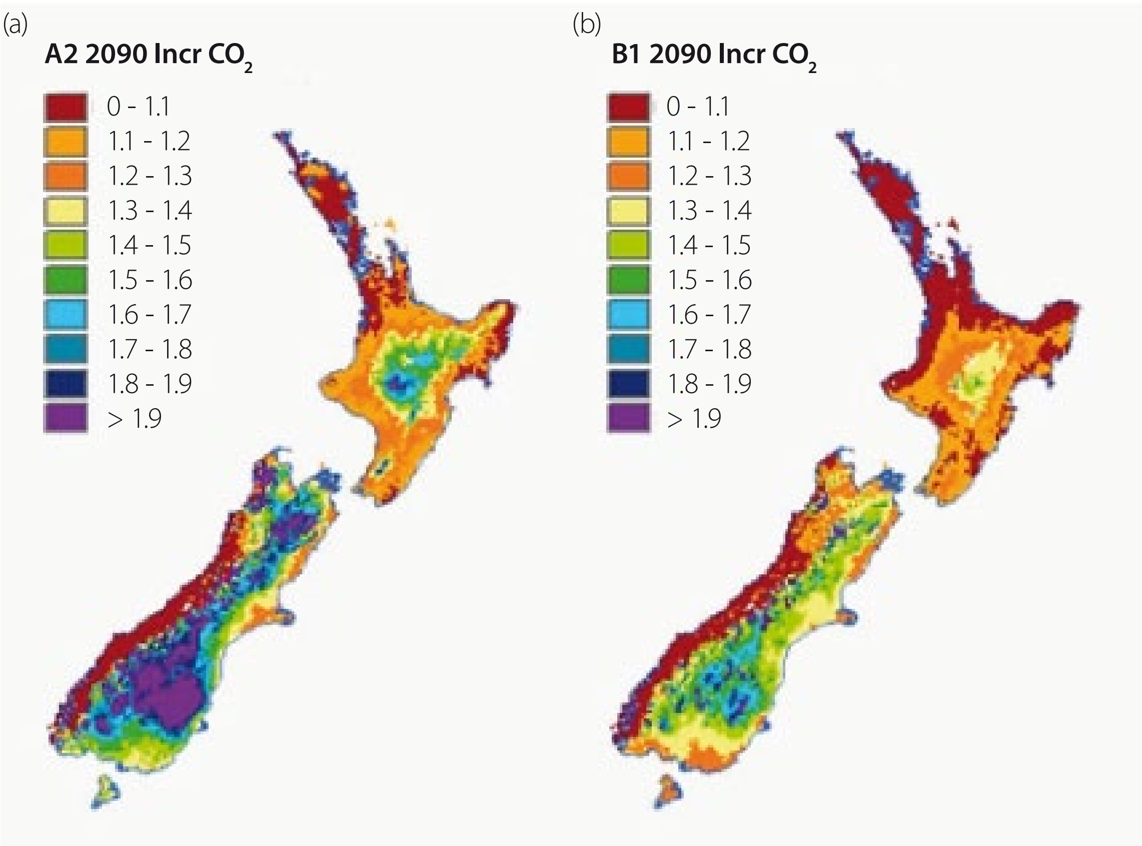

Figure 7.5. Relative change in volume productivity for 2090 compared to 1990 under increasing CO_2 concentration. (a) A2 – High emission scenario. (b) B1 – Low emission scenario.

Within the current plantation estate (Figure 7.6), climate change was predicted to result in gains in wood productivity in a slight majority of plantations to 2040 (62% with growth gains) and 2090 (54% with growth gains). On average productivity increased by 3% in both 2040 and 2090. Even though the mean change was the same in 2040 and 2090, the range in productivity changes widened between 2040 and 2090. By 2040, the modelling showed that more than 99% of plantations had productivity changes of between –7.5% and +17.5%; whereas by 2090 the range had widened to –22.5% to +32.5% (Figure 7.6).

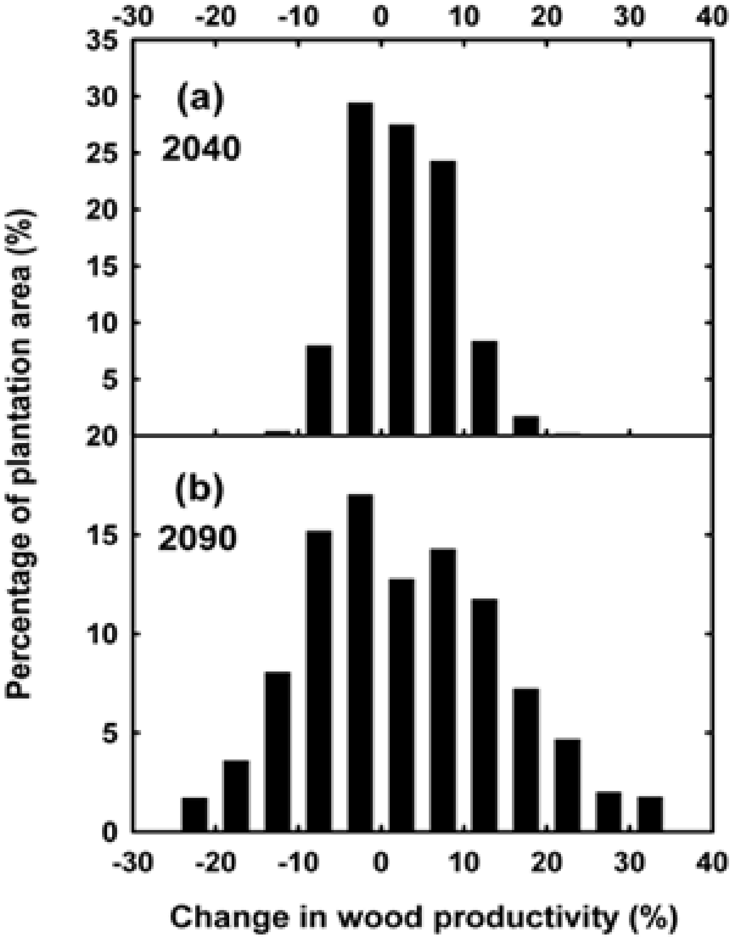

Figure 7.6. Frequency distribution of the current radiata pine estate experiencing specified wood productivity changes for runs with constant CO_2. (a) By 2040. (b) By 2090. The frequency distribution was obtained from relative changes for locations within the currently planted estate for all 36 future climate possibilities (12 GCMs x 3 emission scenarios).

3.3.4 Climate change simulations with increasing CO_2 concentrations

Simulations that included increasing CO_2 concentrations resulted in positive impacts on wood productivity across all emission scenarios for both 2040 and 2090 (Figure 7.7). Increasing CO_2 completely offset the losses in the North Island that had been predicted by simulations with constant CO_2 concentration. With increasing CO_2 concentrations, there were productivity gains throughout the North Island, especially in the higher-elevation Central Plateau. For the South Island, increases in wood productivity were even larger as the stimulatory effect of elevated CO_2 concentration added to the positive effect of warming to lead to substantial overall productivity enhancements (Figure 7.7).

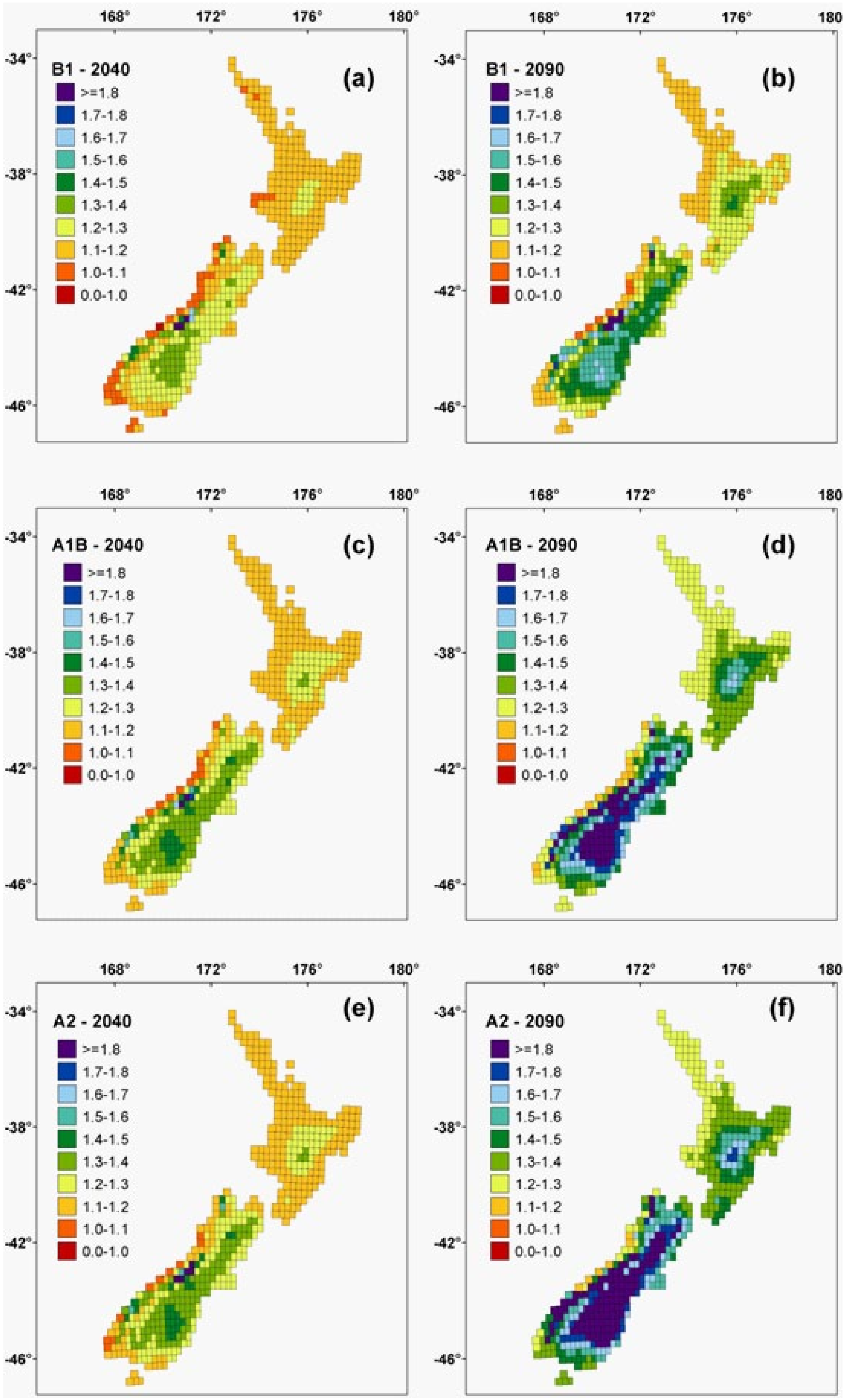

Figure 7.7. Climate change impacts on future wood productivity to 2040 (a, c, e) and 2090 (b, d, f), under the B1 (a, b), A1B (c, d) and A2 (e, f) emission scenarios. The simulations used increases in CO_2 concentrations as anticipated under different scenarios. Results are expressed as the ratio of future wood volume productivity over current-day productivity.

The climate change response was dominated by the productivity response to increases in temperature and CO_2 concentrations, because expected changes in precipitation in New Zealand are generally only minor. In areas such as the upper North Island where rainfall is expected to decrease and temperature to increase, this would lead to increasing water stress and decreased productivity if there were no changes in CO_2 concentrations (Figure 7.3). However, increases in CO_2 concentration are likely to avert developing soil-water shortages and lead to overall productivity enhancements – even in areas where precipitation may decrease slightly.

Productivity gains were found for over 99% of all plantations in both 2040 and 2090 (Figure 7.8). On average, productivity increased 19% by 2040 and 37% by 2090. Both the average and range of these gains increased markedly from 2040 (from –5% to +35%) to 2090 (from –5% to +95%). Very few sites were expected to experience reductions in productivity, because anticipated changes in precipitation were slight and few sites in New Zealand are likely to experience temperature increases into a range that would be detrimental for the growth of radiata pine.

Marginally adverse changes in temperature or rainfall, especially where they would reduce potential water availability, were negated by the effect of increasing CO_2 concentration. At the same time, there were a small number of sites where beneficial changes in precipitation and temperature combined with the response to increasing CO_2 concentrations to result in substantial productivity gains (Figure 7.7).

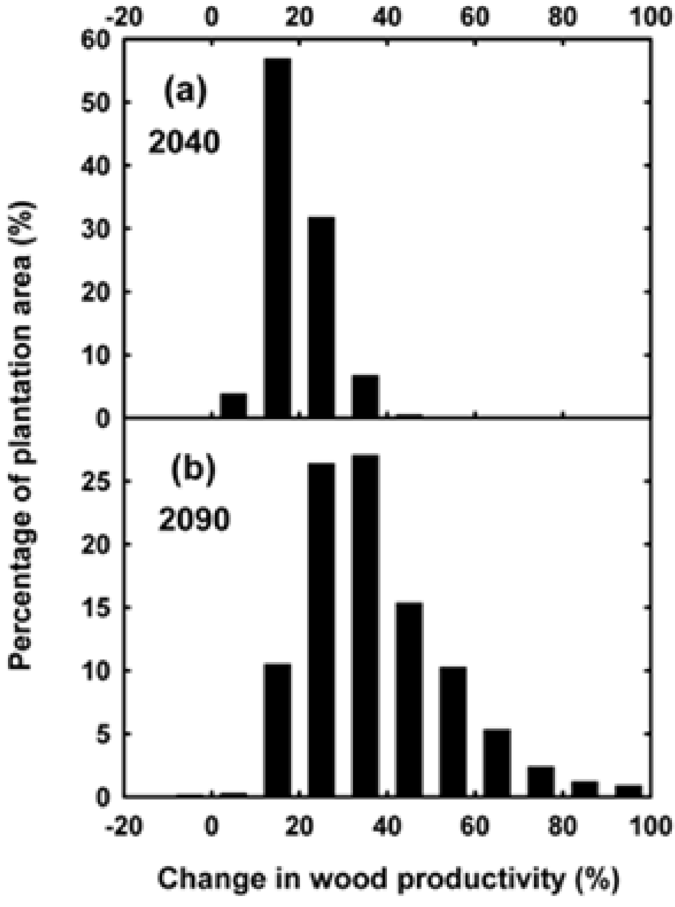

Figure 7.8. Frequency distribution of the current radiata pine estate experiencing specified wood productivity changes under simulations with increasing CO_2 concentrations. (a) By 2040. (b) By 2090. (b) The frequency distribution was obtained from relative changes for locations within the currently planted estate for all 36 future climate possibilities (12 GCMs x 3 emission scenarios).

These simulations highlight the potential response to increases in enhanced CO_2 concentrations as a key determinant of future productivity of radiata pine within New Zealand. The modelling work dealt with the uncertainty surrounding the response of plants to increases in CO_2 concentrations by presenting simulations that bracket likely extremes. With CO_2 concentrations kept constant, the mean climate change responses were varied, with moderately negative responses in the north and moderately positive responses in the south (Figure 7.3). When CO_2 concentration was increased, the model projected substantial gains throughout the country (Figure 7.7).

The magnitude of growth gains under increased CO_2 concentration clearly interacts with other environmental conditions. Greatest growth gains are likely to be found on warm sites with adequate nutrition, but where water is limiting, so that the growth response to CO_2 can shift from a direct photosynthetic response to a dependence on the (more substantial) increase in WUE (Kirschbaum 1999b; Körner et al. 2007) related to stomatal closure under elevated CO_2 concentrations(Medlyn et al. 2001). As most of New Zealand has relatively fertile soils and moderate to good water availability, the effects of increasing CO_2 concentrations are ubiquitous – but generally only moderate. Greatest gains are likely on dry-land sites, located in eastern regions of both islands (Figure 7.7).

Box 7.3. The effects of carbon dioxide fertilisation under the Primary Sector Adaptation Planning Scenarios.

The newer (PSAS) scenarios have also made it possible to generate time courses of changes for about 100 randomly selected sites. Figure 7.9 (top panel) compares the mean cumulative response (in red) with the mean of individual site responses (in blue) shown for simulations with CO_2 concentration held constant. It shows that the cumulative total changes more negatively than the mean of individual responses. It means that some sites with low productivity and thus little contribution to the overall total productivity can be more positively affected by climate change than the effect for already more productive sites.

There was also much variability between sites, with some stands affected positively and other negatively. Figure 7.9 (bottom panel) shows the mean productivity response and the pattern of change for two sites with similar 1990 productivity, but shows the changes for the sites that are most positively and most negatively affected over the next 100 years. For the most beneficially affected site, productivity was simulated to increase from about 22 to 28 m^3 ha^{-1} yr^{1}; whereas for the most adversely affected site, productivity increased until about 2020, but then started to decline sharply, with a productivity of only 13 m^3 ha^{-1} yr^{1} by 2090.

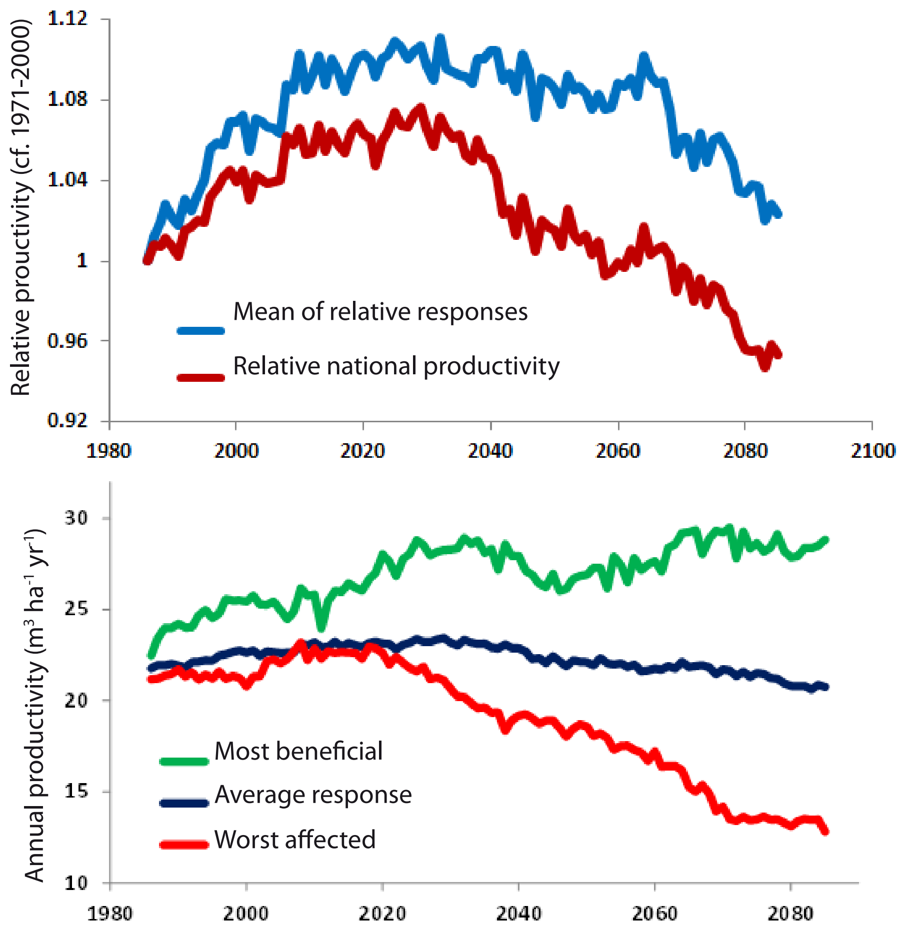

Figure 7.9. Time course of simulated wood volume productivity change under the A2 scenario and with constant CO_2. (Top) relative productivity. (Bottom) Annual wood volume productivity.

The variability in projections is shown further in Figure 7.10, which gives the mean productivity change for our randomly selected sub-group of sites together with the standard deviation of productivity changes. While mean productivity changes little over the next 100 years, individual sites could be greatly affected, with widening variability into the future. While there is a same minor mean productivity change under both the A2 and B1 scenarios, there is much greater variability under the A2 scenario. For individual land holders it is, of course, of little consolation if the productivity decline that they experience will be compensated for by productivity increases somewhere else (and even more so if those other regions are currently so unproductive that they are not used for growing pines).

The patterns become more positive when increasing CO_2 concentration is also included in the simulations, with mean responses showing a steady increase into the future. The inclusion of increasing CO_2 concentrations does not reduce the variability in the modelled change in productivity, with the standard deviations of the response being similar for simulation with constant and increasing CO_2 concentrations. However, with the overall increase in productivity under increasing CO_2, and despite the wide range of modelled responses, the lower ranges of the distribution does not fall significantly below 1, meaning that only a small number of sites (those falling below the lower standard deviation range) would be expected to experience adverse productivity changes over the course of the 21st century.

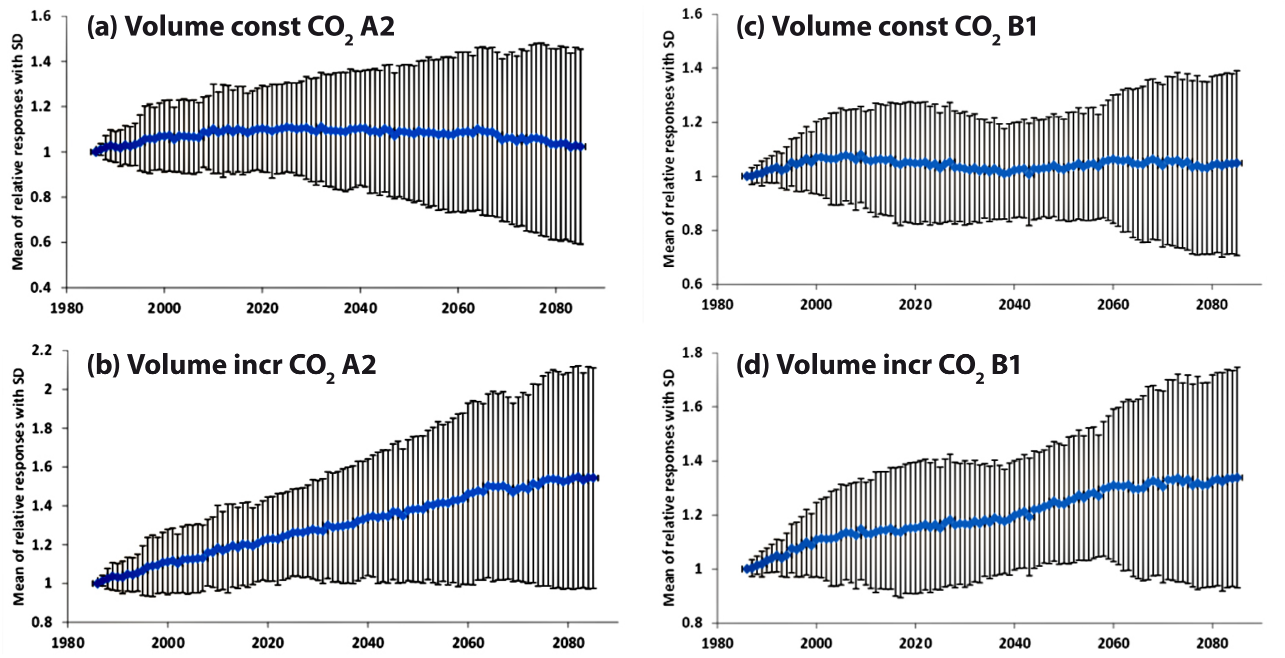

Figure 7.10. Variability of relative wood volume productivity projections under two emissions scenarios, with constant and increasing CO_2 concentrations. (a) High- wood volume A2 scenario with constant CO_2. (b) High A2 with increasing CO_2. (c) Low-emission B1 scenario with constant CO_2. (d) Low B1 with increasing CO_2 concentration. Thick line shows mean values. Bars show the standard deviation of the relative change for all individual sites.

4 Indirect risks to tree productivity

Climate change is expected to affect other drivers of productivity within the forest ecosystem. The risks are: physical (abiotic) risks from wind and fire; biological (biotic) risks of the competitive impacts of weeds, and the destructive impacts of pests and disease.

4.1 Herbivores and pathogens

Insect herbivores and pathogens can cause productivity and value loss and forest degradation. Climate change, primarily changes in temperature and precipitation, can enhance the disturbance caused by insects and pathogens through direct impacts on their growth and development, namely enhancing survival, reproduction and dispersal. Effects can be increased or offset by changes in the growth and development of natural predators, mutualist insects or pathogens and competitors that currently constrain populations. Direct physiological changes to tree defences can also affect the interactions between pests and trees (Ayres & Lombardero 2000).

A typical climate change response predicted is an increase in suitable habitats. Published studies predict changes in species distribution in response to climate change (e.g., Berry et al. 2002; Thuiller et al. 2005). Empirical relationships can be used to predict a range expansion or reduction under different climatic conditions, by defining the current climatic envelope of a species and identifying the new geographic extent based on changes of climate variables under climate change. At the same time, there is debate about the usefulness and limitations of the 'bioclimatic envelope' approach (e.g., Pearson & Dawson 2003; Hulme 2005). Hulme (2005) notes that the 'strongest impacts' of pests on forests are indirect, and arise from biological interactions among species as well as from resource availability, land use and management (Lexer et al. 2009).

4.1.1 Insect herbivores

In order to maintain good forest health, forest managers need to consider any probable changes in insect population dynamics. Climate change is expected to impact the temporal and spatial dynamics of insect populations, as populations of insects are strongly influenced by climate, which modifies the reproduction, dispersal, development, growth and mortality of insect species. Increasing temperature has the greatest influence on forest insect species, causing changes in survival and development rates, which lead to changes to population size and density. Population changes and resultant range expansion modify the interaction between pests and plant hosts and affect the host plants' capacity to resist attack (Bale et al. 2002; Netherer et al. 2008).

Temperature impacts on insect populations arise from:

- The modification of the abundance and distribution of insects and fungi, which is controlled in part by extreme low and high temperatures (Ayres 1992).
- Changes to the frequency of temperature extremes, or sustained increased temperature, increasing the numbers of generations (increasing reproductive potential). This can either destabilise populations or contribute substantially to the occurrence of population outbreaks (Harrington et al. 2001; Hunter 2001; Logan & Powell 2004) as well as increasing over-winter survival (Ayres & Lombardero 2000).
- Changes in climate variability, such as changes in inter-annual variation in minimum annual temperatures, which can be as disturbing as increases in average temperatures (Ayres & Lombardero 2000).
- Occurrence of phenological events earlier in spring under warmer climatic conditions, e.g., adult emergence, peak flight, breeding; or later in autumn e.g., as the start of diapause, hibernation and the departure of migratory species (Parmesan 2006).

Changes in cloud cover, CO_2 concentrations, temperature soil nutrients and precipitation may also affect the success of insect development through changes to the plant host physiology: i.e., where climate-induced stress affects the primary and secondary needle chemistry, changing the needles' resistance to insect infestation and nutritional quality, although it is unclear whether this also will affect food quality (Netherer et al. 2008). Pest species may modify feeding behaviour in order to obtain adequate nitrogen (N) due to reductions in foliar N concentration or under elevated CO_2 conditions (Ayres & Lombardero 2000; Hunter 2001; Johnson et al. 2006).

Indirect effects of climatic change may affect other populations that act as controls on the pest population, allowing for pest population outbreaks. Ayres & Lombardero (2000) identified delayed-density dependencies, often between natural enemies. They suggest from the literature and their own research that southern pine beetle outbreaks could be caused by delayed feedback from a specialised beetle predator or from fungi consumed by larvae that out compete other fungi. Gypsy moth populations are hypothesised to be controlled by a complex dependence chain involving mice populations which feed on the moth pupae, whose population is then dependent on acorn yield. Further controls on moth populations are from viruses becoming more or less pathogenic to caterpillars depending on the caterpillars' consumption of leaf tannins. These secondary relations are complex, and the authors note that mice also carry the Lyme disease tick host, leading to human health issues associated with changes in moth populations. Permanent changes in climate that produce delayed density dependence could make pest outbreaks cyclic, considerably changing disturbance regimes.

Netherer et al. (2008 p. 832) note that 'individual responses of insects to a changing climate and the complex interactions make possible consequences difficult to predict. Intensity and extent of future damage by specific insect herbivores not only depend on the performance of the species, but also on the effects on its natural enemies under the altered climatic parameters, on changes in host stand composition and susceptibility, and on synchrony with host plants and antagonists.'

Pinkard et al. (2010) indicated that the impact of defoliation on production might increase up to 15% under future climates in some Australian radiata pine forests and that there would be considerably more variation in responses than is observed under current conditions.

4.1.1.1 Implications for production from changes in New Zealand insect populations

From the literature, it is only possible to only infer implications. It is expected that temperature increase will change the population dynamics of insect populations currently present in New Zealand and provide habitat for new species currently not present, such as the pine processionary moth (***Thaumetopoea pityocampa***).

The distribution of the pine processionary moth has been projected using a niche climate model – Climex (Sutherst et al. 2007 a, b). Future climate change distributions are projected using three climate change models (GCM) (CSIRO, NCAR, MIROC) under two IPCC climate change (SRES) scenarios: A1B – medium emissions and A2 – high emissions. The GCM data from derived from world climate research programmes coupled model intercomparison project phase 3 multimodal data set (Meehl et al. 2007).

Using Climex, with the current climate, 60% of the total New Zealand radiata plantation area was found to be suitable for the moth, whereas under future modelled climate the geographic range was projected to extend to 93% of the radiata plantation estate. The productivity impacts, ***under current climate***, of the moth establishing in New Zealand are an average volume reduction of 16% over the course of a rotation. Estimated reductions in productivity range from 42.5% in Northland to 0% in many South Island regions, with losses (NPV) estimated at NZ$1.3 billion. With lower rates of dispersal, NPV losses ranged from between NZ$167 million to $500 million. ***Under future climate*** the projected reductions in average volume for all of New Zealand ranged from 29% to 33% between different climate scenarios. The losses (NPV) ranged from NZ$2239 million – NZ$2493 million (Watt et al. 2011.)

Battisti et al. (2005) showed through statistical models and field translocation experiments, that range expansion (both geographical and altitudinal) will occur with increases in temperature. Changes in temperature, in particular, caused early season effects on phenology; and range expansion was related to rises in average winter temperatures, where feeding behaviour of the larva was controlled by previous day temperate reaching 6°C and the night temperature being above 0°C. Increases in temperature increased feeding and reduced starvation periods enhancing survival in previous inhospitable areas.

4.1.2 Disease and pathogens

Climate change and forest disease reviews (e.g., Sturrock et al. 2011 and references within) have shown that, firstly, climate change is likely to affect, pathogens, hosts and their interactions, as pathogen occurrence and growth are strongly affected by climatic conditions changing the impact of disease on the hosts. Secondly, climate change is likely to affect the relationship between the diseases and their hosts' abiotic stressors such as temperature and moisture which affect the host susceptibility to pathogens, pathogen growth, reproduction and infection. This change in relationship could be the biggest driver of disease outbreaks. Thirdly, climate change may change the spatial distribution of diseases as pathogens will be able to colonise new locations.

Pathogens are expected to react to climate change much more quickly than trees due to their mobility and much shorter life cycles. This will increase pathogen-induced forest disturbance. Host – pathogen and host-vector-pathogen interactions may also be affected by climate induced changes to the synchronicity of co-dependent phenological and life-cycle events, potentially changing the severity and incidence of the disease.

Some of the likely specific impacts are:

- Increased impacts, where host species are susceptible to pathogens when the trees are stressed (e.g., by water limitation), if further restrictions in water availability occur under climate change; but susceptibility may decrease if climate change improves water availability.
- An increase in foliar disease impacts due to potentially increased humidity. (This may arise from growth in the size, density and biomass of the canopy, as a result of higher temperatures and elevated CO_2 concentrations thereby reducing any beneficial effects of climatic changes on productivity.)
- Shortening the reproduction period of the pathogen and thus increasing inoculums, resulting in increased

disease prevalence. Conversely, in some circumstances, inoculums may be reduced and disease incidence could be reduced.

- Changes to the rate of spread of a pathogen and its growth caused by changes in abiotic factors such as rainfall, temperature, humidity, wind, and radiation.
- Changes in temperature and water availability affecting the ability of foliar fungi to penetrate the host and complete sporulation (Harvell et al. 2002). Woods et al. (2005) found that increases in summer precipitation resulted in an outbreak of Dothistroma needle-blight in northern British Columbia (Johnston et al. 2006).
- A predisposition of trees to attack from pathogens under drought conditions (Desprez-Loustau et al. 2006);
- Changes to pathogen reproductive capacity caused by changes in rainfall and relative humidity, (Ayres & Lombardero 2000; Chakraboty 2005)
- Surface wetness, temperature and high humidity influencing the process of infection and hence the success of spore infection (Djurle et al. 1996; Margarey et al. 2005).
- Epidemics may become more frequent (Sturrock et al. 2011).

Climate change can have indirect effects on the epidemiology of both insects and pathogens through the effects of climate on other inter-related components of the ecosystems. As well as the type of indirect effect identified in the previous insect section, Ayres & Lombardero (2000) identify disease syndromes that rely on insects as vectors as potential indirect effect. A relevant example to New Zealand is that the distribution of Dutch Elm disease could change depending on the effects of climate on both the disease and also its beetle vector. Ayres & Lombardero (2000), also identify pine canker distribution as dependent on its insect vectors.

4.1.3 New Zealand implications from climate changes on pathogen range

Potential impacts from a range of pathogens have been reported. Dothistroma needle-blight and pitch canker have had their distributions projected using a niche climate model – Climex (Sutherst et al. 2007 a, b). Future climate change distributions were projected using three climate change models (GCM) (CSIRO, NCAR, MIROC) under two IPCC climate change (SRES) scenarios: A1B – medium emissions and A2 – high emissions. The GCM data were derived from world climate research programmes coupled model intercomparison project phase 3 multimodal data set (Meehl et al. 2007).

4.1.3.1 Dothistroma needle-blight

Dothistroma needle-blight is caused by ***Dothistroma septosporum*** and causes defoliation resulting in growth loss but rarely mortality. It is distributed throughout New Zealand, though with differing levels of severity. Infection rates are dependent on diurnal temperatures falling between 5°C and 25°C. Summer rainfall is positively correlated with infection rates. Severe infection occurs with daily mean temperature of between 16°C and 20 °C, a period of wetness of 10+ hours and where more than 2000 spores are present on a needle (Bulman 1993, Bulman et al. 2004). Under a warmer and drier climate the impact is expected to decrease or not change with a medium uncertainty; under a warmer and wetter climate the impact is expected to increases with low uncertainty (Sturrock et al. 2011).

The results from the Climex model projections are that the potentially suitable areas will increase to the entire country under two of the GCM models; while the third model projects a small area in Southland remaining unsuitable (Watt et al. 2011).

4.1.3.2 Pitch canker

Pitch canker (***Fusarium circinatum***) is not currently present in New Zealand. Under the current climate the northern and coastal areas of the North Island have a suitable climate for pitch canker. Under future climate scenarios, the majority of the North Island and northern and coastal areas of the South Island will potentially have suitable climate (Watt et al. 2008). With a warmer and drier climate the impact is expected to increase with a medium uncertainty; under a warmer and wetter climate, the impact is expected to increase but high uncertainty remains around that prediction (Sturrock et al. 2011).

4.1.3.3 Swiss needle-cast

Swiss needle-cast (***Phaeocryptopus gaeumannii***) affects Douglas fir. The symptoms include chlorosis, resulting in reduced retention of needles and growth reduction. It is distributed throughout New Zealand (Hood 2011). Stone (2007) found that the climate variables positively correlated with infection level were a winter mean temperature above 5°C (Hood 2011) (80% variation explained); and that infection is favoured if spring/early summer is relatively wet. Douglas fir is least affected on cooler, higher altitude, inland sites, especially in the South Island (Hood 2011). Under a warmer and drier climate, the impact is expected to not change with a medium uncertainty; under a warmer and wetter climate, the impact is expected to increase with low uncertainty (Sturrock et al. 2011).

Watt et al. (2011) used CLIMEX to predict the abundance of and severity of the disease. They found that under climate change (GCM's CSIRO Mk3, MIROC-H, and NCAR-CCSM forced using A1B and A2 scenarios) by the 2080s, the suitable area in the North Island for Douglas Fir plantations would reduce from the current 100% to between 36% and 64%. This reduction was due to the increasing projected severity of Swiss needle-cast making many areas, at best, marginal for Douglas fir.

4.1.3.4 Armillaria

Armillaria species (***Armillaria limonea*** and ***Armillaria novae-zelandiae***) cause root disease resulting in wood decay, growth reduction and death, particularly in young radiata pine trees. Mortality in radiata pine occurs throughout the North Island and much of the South Island, being most prevalent on ex-native forest sites, but it also occurs at other locations. ***Armillari***a occurs naturally in indigenous beech and podocarp & broadleaf forests. ***A. limonea*** is only known in the North Island and the northern South Island (Van der Pas et al. 2008). The incidence of this disease is expected to increase as temperature increases. With a warmer and drier climate the impact is expected to increase with a low uncertainty; under a warmer and wetter climate, the impact is not expected to change with medium uncertainty (Sturrock et al. 2011).

4.1.3.5 Diplodia

This fungus (***Sphaeropsis sapinea*** syn. ***Diplodia pinea***) is primarily a wound pathogen but can attack tissue under damp conditions. The impact on the current season's growth is the dieback of terminal and lateral shoots. It can also infect stems leading to the death of part of the crown or even the whole tree. Uncommon direct infection of healthy stems has been recorded in Hawke's Bay and Canterbury under conditions of severe drought. Climatic conditions of temperatures between 20°C and 25°C and >90% relative humidity favour the development of infection in green shoots. With a warmer and drier climate the impact is expected to increase with a low uncertainty; under a warmer and wetter climate, the impact is not expected to change with medium uncertainty (Sturrock et al. 2011).

4.2 Weeds

Increasing weed species distribution in forests may result in lower stand productivity due to competition for soil and water resources, as weed species growing under enhanced CO_2 concentrations will be more productive (Howden et al. 2003). Changes in temperature and rainfall patterns may result in colonisation of warm-adapted weed species to new locations as climatic zones shift (Sutherst 2000; Kriticos & Filmer 2007), but restrict pests that inhabit cooler areas (Howden et al. 1999).

Some weeds will respond more strongly to increases in CO_2 concentration and temperature than other plants and may become invasive and dominant in the future. This includes 'sleeper weeds' – those that are present in New Zealand and relatively benign under current climate but which could become significant under climate change scenarios. There is currently not enough information to identify particular species with certainty (Ziska 2003).

An increase in the productivity of weeds and the establishment of new invasive weeds can increase their competitive effectiveness and affect tree survival and growth – especially during establishment and early growth of plantations. This has implications for weed control (Richardson et al. 1993, Richardson & West 1993).

Weed species will also have changed interactions with insects, pollinators, pathogens and disease, which could also affect spread and growth.

There are available tools for modelling the impacts of weed competition such as Vegetation Manager (VMAN). This is a decision support tool which models weed-free tree growth, weed growth and weed response to vegetation management treatments. The weed growth models can be calibrated to any real data for specific site types and allows the cost-benefit of single treatments or treatment regimes to be evaluated using the time gained from the treatment as the benefit. The model is sensitive to competition between the early growth patterns of trees and weeds where small variations in the early weed or tree growth can result in substantial changes in subsequent competition. VMAN allows the sensitivity of tree growth to be explored but relating the results to a particular stand at establishment may be difficult (Richardson et al. 2006; Kimberley & Richardson 2004).

4.2.1 Implications of climate change for New Zealand weed range

The distribution of ***Buddleja davidii*** is projected using the climatic niche model Climex (Sutherst et al. 2007 a, b). The future climate change distributions were projected using three climate change models (GCM) (CSIRO, NCAR, MIROC) under two IPCC climate change (SRES) scenarios: A1B – medium emissions and A2 – high emissions. The GCM data were derived from world climate research programmes coupled model intercomparison project phase 3 multimodal data set (Meehl et al. 2007).

The current projected distribution is across most of the North and South Island as suitable for ***Buddleja***, with unsuitable regions in high altitude part of the South Island. The potential distribution increased under future climate scenarios with large regional variation, particularly in the high country areas of the Southern Alps. The likely areas of invasion are in the east and southern regions of the South island; and also where there is increased climatic suitability and disturbance typically associated with forest management (Watt et al. 2011).

4.3 Soil processes and nutrient availability

Most nitrogen and phosphorus is derived from the decomposition of soil organic matter. Under enhanced CO_2 conditions, in areas of forests that are nutrient deficient (or become nutrient limited), the internal nutrient concentrations will reduce (Drake et al.1997 Tissue et al. 1993) as more nutrients are immobilised in soil organic matter which then reduces the nutrients available for tree uptake (Rastetter et al. 1992, 1997; Comins & McMurtrie 1993; Kirschbaum 1994; Kirschbaum et al. 1998). This will provide a limitation on any productivity from increasing CO_2 concentration. On the other hand, temperature can stimulate the rate of organic matter decomposition and the mineralisation of nitrogen (Kirschbaum 2004). With increasing temperature, more nutrients can become available for plant uptake, and that can stimulate plant productivity independent of any direct physiological effect of increasing temperature (Schimel et al. 1990).

4.4 Effect of climate change on wood properties

Wood properties are related to environmental conditions that affect the rate and seasonality of growth, such as temperature, CO_2 concentrations and water (Watt et al. 2005). A summary is provided below:

- Generally, density decreases with increasing growth rate (Drew et al. 2009), although Downes et al. (1997) found that the density relationship between growth and productivity can be weak.
- Wood basic density is negatively correlated with daily temperature, where there is high soil water availability (Drew et al. 2009).
- Wood density is sensitive to water availability and density increases with decreasing water availability (Drew et al. 2009).
- The inter-annual distribution of rainfall or soil water deficits induced by weed competition affects wood density (Wimmer & Downes 2003; Watt et al. 2005). This is due to difference in the proportion of growth between early wood and latewood cells. Thin-walled early wood growth has a negative relationship with density, whereas thick-wall late wood growth has a positive relationship with density.
- Microfibral angle (MFA), cell wall thickness and modulus of elasticity decreases with water stress in radiata pine (Watt et al. 2005).

4.5 Fire

Fire risk is evaluated as a combination of current weather, ignition sources and fuel loads. Climate changes such as decreasing rainfall, increasing temperatures and more incidences of high temperatures will modify fire risk (Pearce et al 2011; Booth 2009), since:

- Drier fuel can result from higher temperature, reduced rainfall and increased lower relative humidity (Hennessy et al. 2005; Matthews et al. 2009).
- Litter production and decomposition rates under enhanced CO2 concentrations can modify the fire fuel loading where increased temperature increases decomposition rates of both leaf litter and woody debris rates – provided there is adequate moisture (Mackensen et al. 2003; Hyvonen et al. 2007) reducing fuel loads
- Decrease in litter decomposition occurs when C:N ratios are increased (Hyvonen et al. 2007), increasing fuel loads.
- Increased natural ignition from projected increases in thunderstorms frequency (Steffen 2009).
- The productivity and spread of weeds increases with climate change, providing more natural fuel.

4.5.1 Fire in New Zealand

Wildfires in New Zealand can generally be characterised as high frequency events with low to medium severity. However, there are also periodic 'catastrophic' wildfires that occur less frequently but have much more devastating consequences.

Wildfire occurrence and climate are intimately linked, at daily, seasonal (e.g., drought, El Niño-Southern Oscillation events) and much longer time scales (e.g., decadal oscillations, climate change). The impacts of climate on fire (adapted from Watt et al. 2008) are:

- An altered fire frequency and severity (Overpeck et al. 1990; Nitschke & Innes 2008).
- An increased fire activity as a result of both natural (Nitschke & Innes 2008) and anthropogenic ignition (Wotton et al. 1993, 2003).

These impacts can result in:

- Increased incidence of escaped fires (Torn & Fried 1992; Fried et al. 2004).
- An increase in area burned (Flannigan & Van Wagner 1991; Flannigan et al. 2003).
- Longer fire seasons (Wotton & Flannigan 1993).
- Higher suppression and fire management costs (Flannigan et al. 2009).

In New Zealand the impacts (Pearce et al. 2011) are:

- Fire climate severity is likely to increase due to increasing temperature, wind speeds, and lower rainfall or humidity in:
- the east and south of the South Island, especially coastal Otago and Marlborough and south-eastern Southland
- West of the North island
- Under extreme model scenarios, increased are projected to occur in the lower North Island and the Bay of Plenty.
- Fire danger may decrease in some areas by 2080s or be unchanged due to increases in precipitation in:
- The West coast of the South Island
- Western areas of the North Island, such as Taranaki

- East Cape
- Coromandel.

But, under some models, there are projected decreases in parts of Canterbury, Northland and Southland.

- the length of the fire season will probably increase in parts of the country
- increased fuel drying caused by increases in drought
- greater number of fires and intensity as drier fuel increases ignition
- faster fire spread, increased areal burnt with drier fuel and higher and drier winds
- increased fire fighting costs.

Forest productivity impacts from fire damage will be exacerbated through interactions with other climate change impacts such as:

Drought (Mullan et al. 2011).

Changes in the extent and distribution of weeds with climate change providing more flammable fuel types, especially through more flammable plants and plants that provide a higher fuel load such as woody scrub (e.g., gorse, broom) and grass species.

Increase in favourable habitat for insects in fire-damaged forest areas, (e.g., bark beetles; see Bradbury 1998; Suckling et al. 2001), leading to more insect outbreaks and greater damage to forest areas adjacent to burnt areas.

4.6 Wind

Wind is a significant physical risk to planted forests with a history of 500 years of damage events in New Zealand (Thompson 1976; Somerville 1980, 1995; Moore et al. 2011), with estimates of present net worth reduction of 11% given 1% (area) of annual damage (Manley & Wakelin 1989).

The two main forest management activities which have the potential to increase the risk of damage are thinning and felling. These activities increase the wind exposure to the residual trees and have been associated with a considerable amount of the past damage in New Zealand forests (Moore 2011).

Risk of damage to stands is based in the interaction between the vulnerability of a stand to toppling or breakage (as measured by the wind speed) and the wind climate.

Under climate change, for stable stands that have a high critical wind speed, small to moderate changes in the strong wind climate may only have a negligible impact on the risk of damage. However, for those stands which have low critical wind speeds, even relatively small changes in the wind climate could have a large impact on the risk of damage. If the wind climate becomes more variable, then the risk of damage will increase. (Moore et al. 2011).

Modelling projections of changes to wind under climate change is problematic, as it can vary significantly over short distances and time periods. A consistent signal from the climate projection is that there will be an increase in westerly wind circulation especially in winter and spring, but this may reduce in summer. This drives the projected increase in mean annual precipitation in the west and the decrease in the east (Chapter 2, Section 4.2.1).

4.7 Storm and extreme events

Storm events, typically characterised by intense rainfall – when large quantities of rain fall over a short time frame – can have highly detrimental effects on erosion.

In a detailed analysis of future wind extremes under climate change (Mullan et al. 2011, p 74) the projection is that 'the frequency of extreme winds over this century is expected to increase in all regions in winter and decrease in summer'. In particular:

- zonal type winds are projected and an increase in winter extreme wind frequencies having most influence in Canterbury, Otago and Southland

- blocking weather types could increase extreme summer winds in Northland, Coromandel, Bay of Plenty, Gisborne and Taranaki, with the opposite effect in winter
- cyclone (low pressure centres, not tropical cyclone) intensity is expected to decrease over New Zealand, though intensification could occur south of the New Zealand during winter, leading to a stronger pressure gradient over the South Island and an increase in extreme winds in the South Island.

Analysis (see Chapter 2, Section 3.2.3) of the last 20–30 years rainfall data has not detected any increase in hydrological cycle. A detailed study (Chapter 2, Section 3.2.3) found no significant variation in total annual rainfall or in the occurrence and intensity of extreme precipitation events in the Waikato region over the 1900–2007 period. The guidance provided for New Zealand (Chapter 2, Box 2.5) is to plan for an 8% increase in rainfall intensity per degree of warming.

4.8 Erosion

Slope is a major factor in soil movement, with 73% of landslides occurring on slopes of between 25° and 35°. In shallower soils, slopes over 30° become unstable when they become saturated and there is no substantial reinforcement from competent root systems (Crozier & Eyles 1980; Rogers & Selby 1980; O'Loughlin et al. 1982a, b).

New Zealand has about 20% of its plantation forests in steep (> 20°) hill country which is highly erodible and susceptible to extreme weather events (Marden & Rowan 1995; Fransen et al. 2001).

It is expected that if extreme events of rainfall occur over areas of erodible soil or on steep slopes, under the projected increase in the frequency of such events, occurrences of slippage will also increase. The High Intensity Rainfall Design Systems (HIRDS) can be used to estimate rainfall frequency across New Zealand (see: www.niwa.co.nz/software/hirds).

5 Adaptation

Under the projected climate change scenarios, forestry will have to adapt to:

- increase in mean annual temperature of 0.9°C by 2040 and 2.1°C by 2090
- a shift in the daily temperature frequency distribution to a higher temperature, with fewer cold temperatures and more higher temperatures
- a change in rainfall distribution in New Zealand, with substantial variation within the country and with season
- an increase in the extreme rainfall events from zero to half current return periods by 2040; and a zero to fourfold reduction in return period by 2090
- changes in the wind environment, increasing westerly flow by 10% by 2040
- increase in strength of winds by 10% by 2090
  (Adapted from Ministry for Environment (2008), See also Chapter 2, Table 2.4)

Adapting to the effects of climate change by forestry is complicated by:

- having to work with uncertainties in projections (i.e., the quantum of impact of climate change on production at specific locations)
- uncertainties in the scale and temporal and spatial distribution of impacts
- the compounding of uncertainties along the climate change impact 'chain', from the uncertainty in the projection of change through to uncertainties in the impacts (Dovers & Hezri 2010)
- cases where the magnitude and likelihood uncertainties of the secondary impacts of climate change can only be qualitatively estimated at best, as having 'low agreement' and 'medium agreement' on the magnitude and likelihood of damage (Dovers & Hezri 2010)
- potential lack of agreement on options for adaptation even where the degree of climate impacts are

understood and agreed, as there can be many potential different adaptation options (Dovers & Hezri 2010)

- The decision making for adaptive response exists within political environments (Government and private sectors) where non-scientific sources of uncertainty (e.g., distortion, deemed irrelevance, intentional bias, lobbying and confusion) exist that reduce the impetus for change (Dovers & Hezri 2010)
- an unknown future economic environment.

Forestry has a long crop rotation length of about 28–30 years. Adaptation for forestry needs to understand impacts arising from the current climate variability, the observed medium- and long-term trends in climate and its variability and the projected change in climate over the long term (Adger et al. 2009). Radiata pine plantations established currently – and future plantations or re-plantings - will be growing in an uncertain changing climate where adaptation options become more limited as the crop grows (Pinkard 2010). Business risks are higher where significant site-specific climate change could reduce productivity through the primary and secondary factors discussed previously. Business opportunities arise as increases in temperature and CO_2 concentration may make sites more productive: especially those without water or nutrient limitations for radiata pine; and also for other species and other forest-based businesses. Forestry risk management needs to review the vulnerability, impacts and risks especially for new forest. Adaptation planning is also required in 'anticipation of future climate likelihoods, especially for slow reactive biological systems such as forests' (Spittlehouse & Stewart 2003).

5.1 Barriers to adaptation

A workshop (Moore et al. 2011) and a sector survey (Payn et al. 2009) identified barriers to developing appropriate responses to the sector to climate change. Three major barriers were identified:

- **Low level of awareness**: The sector wants fuller understanding of climate science and uncertainty.
- **Understanding of risk and impacts**: The sector wants a full understanding of the impacts and risks associated with climate change on forest management and productivity, including local and site specific information.
- **Adaptation planning**: Changing risks and opportunities associated with climate change require forward planning and mitigation by forest managers.

Pinkard et al. (2010) also identified the following as barriers to implementation:

- **Lack of tools.** There is a lack of tools to assist with the risk identification, assessment and evaluation of climate change impacts on productivity. Suggested tools are needed to assist in :
- identifying high risk sites
- identifying adaptation strategies that are specific forest operation, and the role of adaptation in managing risk
- ensuring that adaptation does not result in unintended future maladaptation
- dealing with uncertainty
- assessing the economic implications of different adaptation options.

5.1.1 Adaptation strategies around barriers to implementation

5.1.1.1 Low level of awareness

The workshop (Moore et al. 2011) identified a learning series of learning goals that are being implemented through funding from climate change technology transfer contracts. The MPI Demonstration Forests contract provides for workshops and e-workshops on climate change and for co-development with the forestry component of the MPI funded programme on resource development. This also has a learning package component that will address the suggested learning issues.

In summary the workshop summarised the learning framework as:

> What is happening and why, how will – , or how could it – affect me in the short-term and long-term and what could I being doing about it?

Further learning has been identified, that also has impacts on climate change and adaptation, albeit and a large additional benefit. Several themes for learning by the sector have been identified where there is a need to refresh and educate sector professionals on new advances in forest management research (Box 7.4). The topics include: Quantitative silviculture, nutritional management and resource assessment.

Box 7.4. Broad learning themes for building resilience to climate change.

Theme 1: Understanding climate change science

- basic climate literacy
- understanding climate change scenarios
- understanding of how uncertainty
- understanding the difference between weather and climate.

Theme 2: Understanding climate change outcomes

- understanding risks and consequences to forest productivity
- how climate change may affect sites
- how to evaluate and factor in risk to forestry of climate change scenarios.

Theme 3: Adaptation

- incorporating climate change vulnerabilities and adaptation into risk management
- developing mitigation/adaptation strategies across forest management practices including species/genotype selection, pest management, silviculture, harvesting and road planning
- understanding maladaptation.

Theme 4: Specific impact

A series of specific climate related issues were identified as important to the sector, they are:

- wind, rain and extreme weather events
- forests and water yield & water quality
- fire
- change in distribution of pests and diseases
- location of new forests
- species selection
- future growth and yield prediction.

The opportunities under a changing climate of interest are:

- productivity increases
- bioenergy production
- carbon forests (excluding the ETS)
- location of new forests
- species selection.

5.1.1.2 Localised understanding of risk and impacts

A risk assessment process was used in the workshop to evaluate the risks. Application of such a framework to estimate the magnitude and probability of risk lead to a formal evaluation of whether the risk is tolerable; and whether adaptation strategies need to be developed (Figure 7.11).

GIS tools can be used to map risks. A GIS project currently in development allows for scenario testing across a range of different projected climate impacts (MyLand, West, G., Scion, 2012, pers comm.; Watt et al. 2012), the spatial distribution of risks from wind damage, some diseases and the changes to radiata productivity.

A additional option is the use of multiple criteria decision making (MCDM) methodologies to allow users to weight the magnitude and probability of site specific risks occurring and then determine an overall 'risk index' for a site (Paul T. Scion, 2012, pers. comm.).

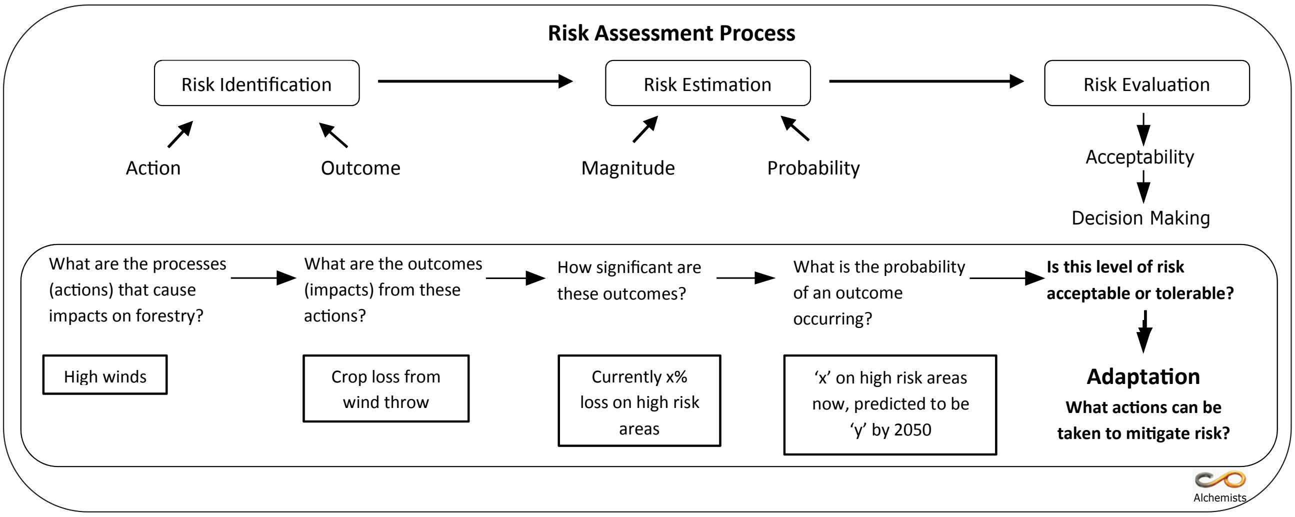

Figure 7.11. Assessment process to determine acceptability of risk and level of adaptation actions required.

5.1.1.3 Adaptation planning

Adaptation planning for forestry is split across the three management planning horizons (Chapter 1, Section 3.1) tactical, strategic and transformational. Adaptation planning operates at different temporal scales of:

- current climate variability
- observed medium and long term trends in climate and its variability
- projected change in climate over the long term (Adger et al. 2009).

These three temporal scales are coupled with the management planning horizons. Typically, the tactical adaptation strategies will focus on the immediate (i.e. current) climate variability through to an expected climate environment as the forestry stand matures and is harvested. Strategic and transformational adaptation strategies are focussed more on the medium- and long-term climate projections; and also on institutional adaptation and areas of significant knowledge gaps.

Adaptation strategies have been derived from the literature (Seppala et al. 2009; Janowiak et al. 2010; Pinkard et al. 2010) and local knowledge, and are organised by forest management actions. These are provided in a series of tables in subsequent sections.

5.1.1.4 Lack of tools

Tools can be developed to assist in aspects of identifying, assessing and evaluating risk and adaptation options.

Identifying high risk sites. Tools for assisting in classification of high risk sites are being developed in the Climate Change module of MyLand and the MCDM analysis tool currently being developed. GIS and spatial analysis can be used to map and aggregate different levels of risk and opportunities where risks levels of all sites could be quantified.

Identifying adaptation strategies appropriate to a specific forest operation and the role of adaptation in managing risk. An MCDM approach, where not only are the weights of risks identified but also any benefits from adaptation impacts, could be used to evaluate the site-specific effectiveness of different adaptation options. However, the effectiveness of this approach is reliant on the accuracy of the relative weights assigned to the different factors.

Assessing the economic implications of different adaptation options. Options for tool development include economic forecasting tools and tools for developing site-specific estimates of cost or risk. GIS can be used to develop cost and revenue surfaces that include basic discounting (e.g. Barry L., & Harrison D, Scion, pers comm, 2012).

5.2 *Risk impacts and opportunities across the growing value chain*

The potential impacts of climate change on forests are organised by different forest operations across the growing value chain (Table 7.2). Each forest operation is discussed in more detail in the following sections. Corresponding tables provide more detailed impacts and risks and provide ***potential*** adaptation options from the literature and the authors as tactical, strategic and transformational.

Table 7.2. Potential climate impacts on selected forest operations and generic risks. Asterisked items (*) are the main climate drivers of risk and impacts. Sources of adaptation options are Pinkard et al. (2010) and Seppala et al. (2009).

	Increasing temperature	***Increasing rainfall***	***Decreasing rainfall***	***Increasing wind***	***Increasing wind and rainfall***	***Increasing CO_2 concentrations***
Forest operations						
Site selection	*	*	*	*	*	
Species selection		*	*	*	*	
Establishment	*	*	*		*	
Silvicultural and forest management				*	*	
Fire management	*	*	*	*		
Pest and Disease Management	*	*	*	*		
Weed Management	*	*	*			*
Forest operations (infrastructure and harvesting)		*			*	
Estate planning						*
Generic Risks						
Productivity risks						
Ecosystem services		*		*	*	

5.3 *Site selection*

Site selection is the process for identifying optimal sites for future forests, categorising exposure of current forests to climate change risk and to opportunities for increased productivity or profitability.

Forest sites can be categorised (adapted from Pinkard et al. 2010) as:

- sites that will no longer be profitable under future climates with current breeding stocks
- sites where current species may grow but require additional interventions to maintain productivity
- sites where growth may remain at current levels or be enhanced by climate change (current species)
- sites where growth could be more affected by biotic and abiotic factors such as pests, wind and fire
- greenfield sites for new timber forests, with current species and alternative species
- sites for new forest business (e.g., carbon forests, bioenergy).

The site selection strategy requires spatial-based, site-specific knowledge of climatic impacts and disturbances with degrees of certainty (e.g., Janowiak et al. 2011). Large spatial scale evaluations (e.g., regional council scale) can broadly classify areas that may be more productive and areas of specific increased risk including those that could respond cost-effectively to adaptation strategies.

Relocation of existing plantations is an option for forests that would qualify, and be economic, under any offsetting policy adopted by Government.

Table 7.3 summarises the impacts/risks to site-selection from climate change and presents a range of tactical, strategic and transformational adaptation options.

Table 7.3. Site selection adaptation options for forestry site-selection.

Risks/Impacts	***Climate drivers***	***Adaptation – Tactical***	***Adaptation – Strategic***	***Adaptation – Transformational***
Changes in growth and productivity result in three site types: **(1) Sites that will no longer be profitable under future climates with current breeding stocks**	All		Risk assessment tools to identify new sites based on growth rates and risk from weeds, drought and pests, for offset and new forests	Current forest optimal land use review, Long term site exit/relocation strategic planning Genetic and breeding for climate resilience
(2) Sites where current species may grow but require additional silvicultural interventions to maintain productivity	All	Growth monitoring and climate monitoring	Silvicultural options Species selection	Current forest optimal land use review. Long term site exit/relocation strategic planning Genetic and breeding for climate resilience Prioritising methods for optimising land use decisions (e.g., MCDM) Economic evaluation frameworks
(3) Sites where growth may remain at current levels or be enhanced by climate change (current species)	All		Silvicultural options	Estate planning incorporating climate change Tools for predicting growth and yield within a more variable climate Quantifying productivity impacts of disturbance
Increased productivity	Increasing Temperature Increasing [CO_2]		Validation of increased productivity under enhanced [CO_2] Regime evaluation Disturbance (including monitoring and intervention) evaluation	Species and regimes for maximum yield & profit

Pest / Disease range expansion, Increased pest productivity and disease incidence	* Increasing temperature, humidity	Identification of pests / disease which may expand into my forests Monitoring of any probable pest / disease expansion If permanent change or occurrence increases 'significantly' then: Identification of pests /diseases which may expand into my forests Monitoring of any probable pest / disease expansion		New control measures New incursion response options Pest range modelling and monitoring Quantifying productivity impacts of biotic disturbance
Weed species productivity increases		DSS tools (e.g., VMAN)		Research into quantifying productivity impacts of disturbance
Erosion	Increasing rain Increased storm events Increasing wind	Identification of high risk areas of erosion of (1) areas of under mature trees (2) Areas harvested for harvested areas Harvest timing (dry season) Quick post-harvest crop establishment		Research options for less intensive harvesting[2], slope stabilisation Replanting options that replace root binding
Flooding	Increasing rain	Methods for drainage Exclusion Flood tolerant species Set-aside as wetlands Mapping and sensing to detect and map flood zones		Research into quantifying productivity impacts and frequency of flooding Land use change
Water logging	Increasing rain		Species selection Genotype resistance	Research into quantifying productivity impacts of saturated soils Land use change Breeding programmes (depends on the areal size of impact)
Drought	Decreasing rain		Land mapping of at risk areas Species selection Genotype resistance	Research into quantifying productivity impacts from drought Land use change Breeding programs
Wind throw and toppling	Increasing wind		Mapping of risk severity across forests and potential forest sites Silviculture planning to minimise effects Age class structure in forest to minimise at risk physical environment	Quantifying productivity impacts Land use change
Extreme wind throw	Increasing wind and rain	Management Mitigation options for stream and debris paths	Areas of risk Mitigation options for stream and debris paths Engineering of water drainage	

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.4 Species selection

The current New Zealand forestry estate is comprised primarily of radiata pine with significant Douglas fir plantations in the bottom of the South island. A changing climate may increase the range and growth rates of potential and current plantation species. Table 7.4 shows the range of species selection adaptation options available to deal with the probable risks and impacts of climate change.

Table 7.4. Species selection adaptation options.

Risks/Impacts	Climate drivers	Adaptation – Tactical	Adaptation – Strategic	Adaptation – Transformational
Geographic range changes for radiata pine and other species	All that impact on productivity		Site suitability mapping and analysis	Genotype and species selection is done with consideration of a changing climate over the rotation length of the plantation[1]
Climate change improves [potential] productivity of other species	All that impact on productivity	Growth trials	Silviculture management of alternative species Market understanding of new products Site suitability mapping and analysis	Breeding programs to examine new alternative species and tradeoffs[1] Alternative species can be selected on the basis of better adaptation to more risky climate / environmental zones[1] Impacts of new productions on downstream processing
Increased risk from biotic disturbances	Increasing temperature		Research into impacts of changes to soil environment and processes Site suitability mapping and analysis	Breeding programs to improve water use efficiency, pest resistance, and competition[1] Genetic modification to enhance resistance or biological efficiencies
Areas may not support plantations of radiata or Douglas fir. e.g., Limitation of Douglas fir plantations in the North Island due to Swiss needle-cast			Site suitability mapping and analysis Change silviculture (e.g., regimes, rotation length) to allow for establishment of known alternative species Forest disestablishment	Breeding programs for climate resistance genotypes[2] Programs for developing climate resistance genotypes using genetic modification[2] Breeding programmes to improve water use efficiency, pest resistance and growth under more extreme environments [1] Identification of new species for at risk areas of land Relocation of forests away from unsuitable land
Reductions in radiata pine productivity			Evaluate the use of genetic material selected on the basis of historical growth	
Impacts of productivity changes on wood quality				Breeding programs for climate resistance genotypes

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.5 Establishment

Seedlings can die or have their growth rate reduced at the time of establishment as they are susceptible to water availability and competition from weeds. Tactical adaptations are focussed on using site preparation techniques which may minimise water loss and weed establishment and different handling; and transportation options so as to maximise the planting of un-stressed seedlings. Strategic options include investigating and implementing any more advanced options for growing seedlings as well as any potentially new handling, site preparation, and transportation options. Other options include the timing of planting to reduce effect of e.g., periods of drought. The transformational options include potential science based methods for changing seedling tolerance as well as using cover crops. Table 7.5 presents a summary of the adaptation options available to deal with the probable risks and impacts of climate change relating to establishment of seedlings.

Table 7.5. Establishment adaptation options.

Risks/Impacts	Climate drivers	Adaptation – Tactical	Adaptation – Strategic	Adaptation – Transformational
Increased mortality due to respiration and water loss	Increasing temperature Less rain Poor water storage	Planting timing[1] Transportation options[1] Hardening[1] Handling procedures[1] Planting options[1] (e.g., water crystals) Weed control[1] Options for soil moisture retention Site preparation[1]	Transportation options Nursery practices for resilience[1] Hardening options[1] Handling options Planting options (e.g., water crystals) Anti-transpirant sprays[1] Using shelter bags[1] Options for weed control[1] Options for retaining soil moisture Site preparation options[1] Timing of planting[1]	Climate monitoring[1] Research and cost-benefit analysis of methods for reducing transpiration in the field[1] Understand the physiological basis of seedling responses to environmental stress to improve capacity to assess risk[1] Select provenances with greater seeding resilience to adverse environmental conditions[1] Cover crops
Increased growth of weeds causing mortality	Increasing rain Increasing temperature	Options for combining herbicide use and cultivation[1] Site preparation options[1] Weed control options	Address any issues of herbicide efficacy[1]	Research integrated weed management approaches[1] Climatic conditions on the window for applying herbicides associated with changing climate[1]
Toppling of tree	Increasing wind	Site preparation[1] Planting methods[1] Seedling age	Forest age structure	
Erosion and slippage	Increasing wind and rain	Site preparation[1] Timing of planting[1]		

[1]Pinkard et al. (2010).

5.6 Silvicultural and forest management

There is a need to consider the impacts that the timing and degree of thinning and pruning have on insect and fungal disease spread, fire loads and risk, impacts from wind damage, and water shortage; as well as productivity. Silvicultural management has been identified as one area where specific actions are required at spatial and temporal scales where climate information is most uncertain (Janowiak et al. 2011.

The USA silvicultural workshop (Janowiak et al. 2011) identified four scales of adaptation response from the broadly applicable to specific options tailored to individual location and conditions (albeit within natural forest management).Table 7.6 summarises these different scales.

Table 7.6. Adaptation response at different scales (Source: Janowiak et al. 2011).

Options	***Strategies***	***Approaches***	***Tactics***
Broad level of adaptation:	Region-specific ecological and managerial responses	Action required by forest	Site specific prescriptions
General←===→ Specific			

At the workshop, when reviewing options for developing regional strategies and forest-based approaches, the question was asked: 'What new or altered considerations does climate change bring to the process of making silvicultural decisions and devising strategies?" A check list, (Table 7.7) developed as a series of further questions was developed. Table 7.8 summarises the adaptation options available to deal with the probable risks and impacts of climate change for silvicultural management.

Table 7.7. Prompting questions for strategic and tactical climate change planning (Source: Janowiak et al. 2011).

Theme	***Prompting questions***
Disturbance	Will susceptibility to some disturbances increase? How will fire affect disturbance susceptibility and frequency?
Migrating climates	Will forests be more vulnerable to increased weather variability? What are the effects of projected changes in temperature range and extremes? What are the effects of projected changes in water availability and timing? Is the future trajectory of forest conditions the same or different under climate change? How long is the lag between the present climate and the future climate?
Habitat manipulation	Is the habitat suitability of preferred species changing/likely to change?
Stress	What stress factors are likely to become more prevalent (e.g., pests, diseases, drought, etc.)?
Competition (weeds)	How will competitive relationships among species change? Will there be increased competition from new species (e.g., invasives, off-site species, etc.)? Can silvicultural practices be used to manage competition throughout the rotation?
Economics	Are there increased costs for needed silvicultural practices? Are there new product markets that can be used for management?
Management objectives and desired future condition	Do the management goals, objectives, or desired future condition need to change? Is the site prescription compatible with climate change projections? How much flexibility is there to change objectives?
Assisted migration	Is there a new or different species that is currently absent that could better meet DFC goals? How do we bridge the gap between near-term and long-term adaptation given inherent species resiliencies and lag times?
Age structure	What is the relationship between tree species longevity and the rate of climate change? Should a different rotation length be considered? Is there a benefit to even-aged or uneven-aged management?

Table 7.8. Silvicultural management adaptation options.

Risks/Impacts	*Climate drivers*	*Adaptation – Tactical*	*Adaptation – Strategic*	*Adaptation – Transformational*
Weed growth after thinning/pruning	Increasing temperature Increasing rain Increasing [CO_2]	Management control options Time of operations Stand density control options[1]	Options for silviculture to manage crown size	Research into weed growth rates, phenology, and control options Review silviculture regime effects on weeds growth and establishment
Increased occurrence and severity of pests and diseases	Increasing temperature Increasing rain		Options for silviculture to manage crown size	
Increased mortality for higher stocking stands in drought zones	Decreasing rain		Stocking impacts on water use in dry periods	
Wind throw after thinning	Increasing wind	Thinning regimes implication for wind risk exposure	Thinning regimes implication for wind risk exposure	

[1]Pinkard et al. (2010).

5.7 Fire management

Fire management strategies should consider the impacts of temperature changes, increase in fuel loads from silviculture, weeds and pest attacks, and changes in the frequency and timing of rainfall and the effects these have on the fire season. Table 7.9 shows adaptation options available to deal with the probable risks and impacts of climate change in the context of fire risk.

Table 7.9. Fire risk adaptation options.

Risks/Impacts	*Climate drivers*	*Adaptation – Tactical*	*Adaptation – Strategic*	*Adaptation – Transformational*
Increasing fire loads – more and drier debris, and weeds.	Increasing temperature, [CO_2], lower or similar rain levels	Conduct operations with a high fire risk (e.g., harvesting) at low fire risk times[1] Manage stocking, debris, weediness and age structure to minimise fire risk[1]	Manage spacing, forest debris, weediness and age structure to minimise fire risk[1] Fire breaks Road side fire options Establish landscape level targets for structural or age class, passive or active measures to minimise the effects or fire, fuel loads, etc	Silviculture regimes to reduce weeds
Increasing fire risk	Increasing Temperature, [CO_2], Wind	Improved detection and monitoring of fires[1] Restrictions on access More firebreaks, ponds etc Wider public road offsets	Improved detection and monitoring of fires, and of factors contributing to fire risk such as thinning and harvest residue, weediness[1]	Landscape-level fire planning from establishment to harvesting to reduce fire risk (fire smart landscapes[1]) Altered distribution of plantations and plantation age classes to spread risk[1] Review location of new forests with respect to fire risk and ignition sources

[1]Pinkard et al. (2010).

5.8 *Weed management*

Weeds impact on growth of trees, provide habitat for pests, are a fuel source and a physical impediment for silviculture. Options for adaptation need to consider the ease at which new species can colonise sites, methods for control, monitoring of weed occurrence and weed prevalence and productivity and the economic impacts of weeds. Options for weed control at all levels are limited. Control mechanisms are limited to developing biological controls, or manual physical removal or spray. Table 7.10 shows the adaptation options available to deal with the probable risks and impacts of climate change in the context of weed management.

Table 7.10. Weed risk adaptation options.

Risks/Impacts	***Climate drivers***	***Adaptation – Tactical***	***Adaptation – Strategic***	***Adaptation – Transformational***
Range expansion	Warmer temperature Change in precipitation	Monitoring Herbicide (establishment)	Options for manual control Growth estimation Economic impact assessment Monitoring methods (including remote and stand-off sensing) Weed growth models Modelling of range expansion Managing forest (post harvest) disturbance Identification of 'sleeper weeds' and management plans	Bio-control Understorey planting that is mutually beneficial and hinders weeds Tree crop genetic improvement for WUE, and light efficiency[1]
Growth rate increase: Competition for water, nutrients and light	Temperature and CO_2 levels increase Precipitation decreases	Weed control options[2] Enhancement of existing biological control	Silvicultural options Managing forest (post harvest) disturbance	
Weed species composition changes	Precipitation, and temperature changes	Weed control options[2] Enhancement of existing biological control	Silvicultural options Managing forest (post harvest) disturbance	
Increase in WUE increasing competitive advantage	Elevated CO_2	Weed control options[2] Enhancement of existing biological control	Silvicultural options Managing forest (post harvest) disturbance	
Efficacy reduction in herbicides	All	Monitoring of effect of herbicides Evaluation of alternative	Silvicultural options Managing forest (post harvest) disturbance	
New Weeds	All	Active management of initial incursion[2]	Identification of 'sleeper weeds' and management plans Active management of initial incursion	Regulatory changes
Buddleja davidii spread		Reduce the spread to the prone eastern and southern regions of the South Island Use Regional Pest Management Strategies to eradicate it Enhancement of existing biological control	Managing forest (post harvest) disturbance	Public engagement in eradication

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.9 Pest and disease management

The response to pests arises from increases in temperature, CO_2 concentrations and rainfall that allow more productive pest growth, pest range expansion and also provides more habitats, increased productivity at younger ages and new pests colonising new areas or as new arrivals to New Zealand. Pest management should consider monitoring methods, including specific protocols for new and economically threatening pests or diseases; biological control for opportunistic sleeper weeds, and methods of eradication or control. More knowledge is required of insect lifecycles, bio-climatic ranges and ecosystem interdependencies to fully evaluate risk. Table 7.11 summarises the adaptation options available to deal with the probable risks and impacts of climate change in the context of pest and disease management.

Table 7.11. Pest risk adaptation options.

Risks/Impacts	***Climate drivers***	***Adaptation – Tactical***	***Adaptation – Strategic***	***Adaptation – Transformational***
Pest population range expansion and increases in pest severity, productivity and vigour	Most that may affect the range and growth cycles of insects, disease and weeds	Forest management options that reduce habitat Weed control Enhance existing bio control Continue surveillance	Enhances (statistical) surveillance[2] Modification of harvest or silvicultural regimes to minimise pest impacts[2] Modification of harvest or silvicultural regimes to maximise tree vigour[2] Establish landscape level targets for structural or age class, passive or active measures to minimise the effects from insects and diseases[2] Development and validation of models that predict impacts of pests under different climate change scenarios Use remote and stand-off sensors for wide scale assessments	Research into pest population growth drivers Research into control/ management options including bio-control Measures of the economic costs of individual pests on production More pest specific knowledge and tools to assess risk and impacts Methods and technologies for remote assessment/ monitoring Develop monitoring options Breeding of resistant genotypes, though with risks that other important traits not selected for can be weakened Assessment of effects of climate change on weed control options Increase genetic diversity of trees used in plantations
New Pests			Risk assessment of overseas economic pests Biosecurity and incursion pathways plans Regulatory controls of weed distribution and sale; and removal in private gardens Monitoring programmes[2]	Proactive eradication, control and management processes and options

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.10 Forest operations (infrastructure and harvesting)

Principally rain and storm events will impact road infrastructure and increase erosion risk on susceptible sites during harvesting and increase impacts of wind on exposed sites. Adaptation strategies are required to minimise the impacts of climate on road design and harvest management through the use of alternative silvicultural and harvesting systems to reduce wind damage, control erosion and enable adequate access for harvesting and post-harvest activities Table 7.12 summarises the adaptation options available to deal with the probable risks and impacts of climate change in the context of forest operations.

Table 7.12. Forest operations adaptation options.

Risks/Impacts	Climate drivers	Adaptation – Tactical	Adaptation – Strategic	Adaptation – Transformational
Erosion risk to roads, and streams **Downstream (neighbourhood) effects**	Increasing wind and rain	Maintain and rehabilitate roads to reduce erosion and sedimentation[1] Action plans for erosion incursions into neighbouring properties	Options for road design, culverts[1] Identification of business and neighbour critical vulnerabilities with action plans Decommission at risk roads	Analysis of erosion risk e.g., SinMap Environmental Standard
Erosion risk after harvest and for the first 7 years after planting	Rain		Minimise impacts from planting roads and skids sites[2]	Develop options for cover crops Site stabilisation – Options for restocking site to build slope stability
Terrain instability	Rain (Soil type)		Minimise/eliminate roads in risk-prone areas, or in catchments with high downstream[2] Limit harvest operations to appropriate seasons[1]	Evaluate erosion risk

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.11 Estate planning

The evaluation of climate change impacts on risk management decisions requires an understanding of the increased risk and uncertainty environment. This requires flexibility, an enhanced capacity for risk analysis, and the assessment of the socio-economics of different planning options, including more strategic and transformational options. Estate planning maybe confounded as many of the planning tools currently used may be inappropriate for dealing with changing climate as they are formulated using historical growth under historical climate (Battaglia et al. 2009; Innes et al. 2009; Seppala et al. 2009). This needs to take into account the climate change specific impacts on forest dynamics and growth, forest inventories and preference functions/ objective (Battaglia et al. 2009).

Linear programming, multi-criteria decision analysis and gaming theory provide frameworks for exploring appropriate adaptation strategies for given climate change scenarios (Pinkard 2010). Battaglia et al. (2009) present a linear programming scenario by Richards & Brack (2004) which modelled a regime under three climate scenarios, allowing managers to explore management strategies and undertake cost-benefit analyses of alternative scenarios.

Estate and tactical planning uses predictive models of growth to determine future yields as it is assumed that growth into the future can be projected from the past. Efforts have gone into models to account for improvements in productivity due to genetic breeding, but there is significant risk in the applicability (accuracy and precision) of current models that assume a constant similar future climate. Research and direct monitoring into the changes in growth, and quality are needed, especially under enhanced CO_2 scenarios (Mason 2009). Table 7.13 shows the adaptation options available to deal with the probable risks and impacts of climate change in the context of estate planning.

Table 7.13. Estate planning adaptation options.

Risks/Impacts	*Climate drivers*	*Adaptation – Tactical*	*Adaptation – Strategic*	*Adaptation – Transformational*
Increased risk from fire, pests and drought[1] **Reduced timber flow due to decreased productivity[1]**	Increasing temperature	Manage stands to promote resilience and enhance productivity[1] Identify implications of extended rotation lengths for wood supply[1]	Develop more flexible forest management plans[1]	Develop management plans that enable changes within and between rotations[1] Develop approaches for management planning, that can explicitly include risk and uncertainty e.g., linear programming, multi-criteria decision analysis[1] Develop products such as biochar, biofuel, carbon forests[1] Explore options for higher-value products/ markets[1] Work with processors and customers to build understanding of climate change impacts on wood supply [1]
Decreased vitality of forests ecosystems due to the cumulative effects of multiple stressors[2]			Monitoring at sub-national and nations scales of all forests across forest health, productivity, invasive weeds[2] Develop test and improve risk assessment methods[2]	
Change in growth rate			Develop new modelling methods that take into account climate/ weather[2]	

[1]Pinkard et al. (2010). [2]Seppala et al. (2009).

5.12 *Productivity risks*

Productivity risks address the risk associated with direct productivity impacts and sink-limitations caused by changes to nutrient availability, precipitation changes, and multifactorial interactions under increased CO_2 concentrations and temperature. Table 7.14 summarises the adaptation options available to deal with the probable risks and impacts of climate change in the context of forest productivity.

Table 7.14. Productivity risk adaptation options.

Risks/Impacts	***Climate drivers***	***Adaptation – Tactical***	***Adaptation – Strategic***	***Adaptation – Transformational***
Changes in growth	Temperature, CO_2 levels			Change regime type to either take advantage of opportunities for fast growth short rotation crops, or minimise detrimental impacts
Changes in growth	Rainfall			Change silviculture regimes to reduce water requirements e.g., earlier and/or production thinning (evaluating risk from wind climate changes)
Nutrient losses	Temperature, CO_2 levels		Use of nitrogen-fixing species as understory, or companion planting Fertilise - use decision support systems to select profitable sites	Quantify impacts of climate on N availability[2]

[2]Seppala et al. (2009).

6 Discussion of adaptation options

Forestry, like most other agribusiness, will have to overcome potentially significant climate-induced impacts on its operations over the next 100 years in order to continue to maximise profitability and growth, and to minimise environmental impacts. Though the projected average changes in climate over the next 30 years are not expected to be catastrophic, more intense climate events are projected to occur along with potential projected changes in impacts from biotic and abiotic stressors or disturbance factors.

New Zealand plantation forestry has prospered alongside the same suite of risks that will be increased with climate change. They are not new risks and are well understood with well-developed risk management (adaptive and reactive) strategies. The advantage of this for many of the risks, is that the strategies only need to be enhanced to take into account any changes in risk profile due to climate change, rather than new strategies having to be developed from scratch.

Climate change also offers a range of opportunities. SKM (2008) undertook a strategic analysis to identify emerging opportunities resulting from the indirect impacts of climate change. For forestry, the report identified the following:

- potential from increased demand in forestry offsets and carbon credits from global CO_2 markets and the ETS, providing additional income to forestry (Kyoto/ETS complaint forests)
- opportunities to develop biochar and bio-oil from pyrolysis of forest residues, and liquid biofuels (e.g., wood to ethanol)
- opportunities to develop biofuels from existing and new forests and short rotation tree crops
- opportunities to develop wood chips using low valued forest products and residues for energy production

- opportunities to supply sustainable wood for building, via an increased use of wood as a sustainable product.

The major opportunity arising from climate change is projected productivity increases of tree species under climate change.

The following sections discuss the adaptation options identified in the previous tables.

6.1 Tactical adaptations

Adaptation for existing forests is constrained by the high level of investment in the existing crop and infrastructure and the long time frame before economic return. This reduces flexibility compared to other land-based sectors and eliminates options for changing forest location and/or species until the end of the rotation.

Short-term climate change risk has limited catastrophic impact, with risks being currently managed using existing risk management processes within companies. However, risk to Kyoto forest carbon credit owners could be higher if they are required to maintain certain levels of carbon stock. Changes in the severity, occurrence, and geographic spread of different impacts as a whole can be catered for within existing risk management methods. Managing effects of extreme events, such as new pests becoming established, or damage from intensive storms are part of the adaptive risk management processes within companies. Typical adaptive strategies of risk minimisation include the modification of silvicultural regimes and the timing of forest operations such as thinning or harvest, manipulating forest age class structure, creating fire-smart landscapes, and the re-engineering of long-term infrastructure to cater for changes in climate. Adaptation to short-term climate variability and extreme events is beneficial, as it is a basis for reducing long-term vulnerability to climate change (Lim & Spanger-Siegfried 2005).

For forest managers located in areas of current low or negligible risk to different aspects of climate change, adaptive strategies would involve re-evaluating risk profiles for risks under different climate change scenarios.

One critical adaptation is the use of more monitoring of forest resources and of the local environment to ensure that changes/impacts are identified well in advance of significant impacts. Current forest management uses risk management strategies such as national surveys of forest disease and insect damage, company nutritional monitoring and ***Dothistroma*** infection assessments.

6.2 Strategic and transformational change

Strategic and transformational adaptation options address in part the knowledge requirements to properly develop and implement adaptation strategies and also to address the changes in the forest growing business environment that may change due to climate change. Typically these would address sites where climate change is projected to be extreme or to change quickly, rendering sites unsuitable or sub-optimal for profitable forestry. This risk becomes significant if the impact of climate change forces a change in economic expectations from forests.

Adaptation options should:

- Increase understanding about risks, impacts, opportunities and adaptation options as quantitatively as possible; this may require new assessment methods for evaluating impacts and (if possible) determining thresholds. The on-going risk assessment needs to manage the uncertainty in accuracy and precision of the magnitude, location and timing of climate change impacts (Spittlehouse 2005).
- Monitor the state of the forest and identify when critical thresholds may be reached.
- Develop capacity for cost-benefit analyses of adaptation options. In most adaptation analyses, to allow decision making on the economic implications of adaptation (Watkiss et al. 2007; Adger & Barnett 2009).
- Understand that adaptation strategies will not resolve all climate change impacts (Seppala et al. 2009, Pinkard 2010).
- Explore how technology can be used or integrated into adaptation strategies.
- Recognise the risk of adaptation generating new problems into the future (Adger & Barnett 2009). Adaptation strategies developed now may not necessarily be optimal by the end of a rotation if climate

change trends or tree responses to climate are different to those we anticipate from current knowledge. Risk of maladaptation can be reduced by building sensitivity analyses into risk management processes and adaptation assessments (Pinkard et al. 2010).

Generally, impacts to forest productivity occur when either biotic or abiotic factors impede biological growth, kill, or significantly damage the crop. Most of the strategic risk options identify the knowledge requirements that are needed to develop suitable adaptation strategies. This is especially important when impacts of climate change can all occur at the same time at the same site, with the tree and ecosystem responses being dependent on the interrelationships between all impact factors, making the total impact assessment more unpredictable and with the impacts varying in severity across forest age and management activity.

6.2.1 Knowledge and tool gaps and requirements from adaptation options

6.2.2 Building natural resilience

A key adaptation option identified in the literature is the development of tree breeds, by either traditional means or by genetic modification, which have heightened resilience (or resistance) to negative impacts, or a better ability to take advantage of improved growing conditions. This includes:

- selecting for improved water management in trees, tolerance to water stress and drought and increasing water use efficiency
- selecting for positive response to increases in temperature and CO_2 concentrations, and for climate resistance in general
- breeding programmes for different productive species
- breeding programmes for pest resistance
- breeding programmes for competition resistance
- breeding for biological efficiency.

6.2.3 Management practices

The adaption options identified components of management practices where either new knowledge is required or implementation of existing intellectual property from either New Zealand or other radiata pine-growing countries management needs to be evaluated. These include:

- new or enhanced establishment methods and nursery practises for new stands grown in sites of drought, low water availability, high temperature and high weed competition
- fire-smart landscapes and fire infrastructure
- the role of silviculture in risk management of pests, wind and fire
- methods of harvesting in risk prone areas
- methods for post-harvest slope stabilisation
- methods and chemicals for control of weeds and pests – integrated weed and pest management approaches.

6.2.4 Climate and climate change impacts

The productivity, biophysical and economic impacts of climate change need to be quantified more accurately in both temporal and geographic terms and at different scales. In summary, more information is needed relating to:

- the long-term impacts on productivity of CO_2 fertilisation and temperature increase in New Zealand for forest productivity (including soil processes and impacts on wood quality)
- changes to the soil biotic and abiotic ecosystem and changes in nutrient cycling, nutrient availability, water retention and soil biota

- the distribution and site specific-risk evaluation of wind and storm events
- economic impacts on tree productivity of pests, diseases, weed competition, disturbance and erosion on forest profitability
- changes to the operational use of herbicides and herbicide efficacy
- integrated quantitative assessment of likely changes in water limitation for plants.

6.2.5 Forest ecosystems and interactions

Little is known about the population dynamics, growth rates, and life cycles of critical components of the biotic forest ecosystems. Knowledge gaps include:

- growth rates of weed species and their phenology
- biophysical growth drivers of pest populations
- impacts on the changes to the population dynamics of pests, diseases and weeds. While work has occurred on bio-climatic envelope modelling, further work is required on this and on pest ecosystem changes
- identification and planning for changes in expansion of sleeper weeds
- planning for impacts, controls and monitoring of new harmful incursions and climate change enhanced pathways or range expansion from Australian-based airborne pathways
- changes to the effectiveness of existing biological control agents.

6.2.6 Forest planning

Climate change may change the growth rate and wood quality characteristics over time, hence planning tools for the future may not be able to use growth data from the past and may have to model CO_2 concentrations, temperature, nutrition, water, competition, disturbance and pests as well as volume growth. Knowledge requirements and tools development requirements include:

further on-going development and refinement of predictive yield models that include climate and the environmental impacts. Monitoring of the forest estate will have to continue, in conjunction with simultaneous monitoring of weather and environment models and/or tools for economic evaluation under climate change and for methods of evaluating adaptation options.

6.2.7 New forests

With suggested productivity increases and range expansion for radiata pine – as well as sites becoming both suitable and unsuitable for long (30yr) rotations –there are opportunities for different forms of production. These could be either long-term carbon forest or short rotation forests for e.g., bioenergy and biofuels forests. The knowledge and tools requirements for these options include:

- understanding site-specific climate impact under different regimes, using different methodologies such as multi-criteria decision making
- species selection
- land use planning.

6.2.8 Monitoring

As the impacts and timing of climate change are imprecise, with varying levels of uncertainty, monitoring of impacts is required to improve understanding, to develop confidence in future projections of climate change impacts, and to evaluate trends in impacts. No monitoring programmes have been developed that are specific for monitoring expected climate change response on plantations, and these need to be orientated to collecting the specific variables that are likely to be responsive to climate change and assessing changes in ecosystem function. Key climate change response indicators could include ecosystem demographics, fecundity, phenology, weather and pest incidence. (Janowiack et al. 2011) Options for monitoring include:

- forest productivity
- distribution of pests, insects and weeds in order to assess range expansion (not just occurrence)
- growth of weed species
- abiotic impacts from wind, fire, and extreme wind events
- water quality and yield.

In summary, forestry has the tools to develop adaptations to climate change. Adaptations will be a mix of tactical, strategic and transformational. Adaptations that affect current forests will be more of the tactical type (e.g., building roads to a higher specification if it is decided risk of extreme storm events has increased). Strategic and transformational adaptations have a longer-term perspective and focus on aspects such as breeding for drought tolerance or developing new energy crops to offset fossil fuel use.

While there are some very straightforward adaptation approaches, forestry faces some very large challenges compared to other primary sectors. These include, for example, the uncertain impact of increasing CO_2 levels on forest productivity. Developing adaptation strategies for crops where the growth cycle is of the order of 30 years and the breeding cycle is of the order of 10–12 years to produce new germplasm, will mean forestry is faced with the need to make large-scale investment decisions based on very uncertain long term outcomes. Putting these adaptation approaches into a financial risk management model would be a logical next stage for the sector as it considers how it will develop and implement any adaptation strategies.

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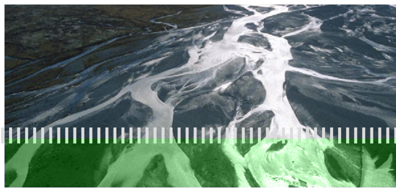
Chapter 8. Water Resources

Water resource impacts and adaptation under climate change



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