Fire Research Report

Quantifying the change in high country fire hazard from wilding trees

Scion

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The effects of wilding conifer spread and their control on fire behaviour have not been previously studied in New Zealand. There is a noticeable lack of research to date on how fire hazards change over time with wilding invasions, or comparing fire behaviour pre and post wilding control. This project aims to provide improved knowledge for fire and land managers on the growth and geographical spread of wilding conifers, and of the impacts of wildings and their control on risk of fires and the potential fire behaviour in high country.

The objectives of this project were to define the geographical distribution of wildings in NZ high country, describe the fire hazards associated with wildings and their control, and transfer knowledge to practitioners to enable effective hazard management.

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Quantifying the change in high country fire hazard from wilding trees

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REPORT INFORMATION SHEET

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EXECUTIVE SUMMARY

Project and Client

This report was prepared for the New Zealand Fire Service Commission Contestable Research Fund. This project aims to provide improved knowledge for fire and land managers on the growth and geographical spread of wilding conifers, and of the impacts of wildings and their control on risk of fires and the potential fire behaviour in the high country.

This final report represents a summary of milestones submitted to the NZFSC.

Introduction

The effects of wilding spread and their control on fire behaviour have not been previously studied in New Zealand. There is a noticeable lack of research to date on how fire hazard changes over time with wilding invasions, or comparing fire behaviour pre and post wilding control.

A wilding invasion present problems not only for land managers in controlling the spread of these wildings, but also has implications for fire fighters and fire managers. Wildfires in these areas could exhibit more extreme fire behaviour, be more difficult to suppress, and present greater threats to lives and property.

It has also been suggested that wilding control methods could increase the fire risk and fire hazard, and threaten life and property in rural-urban communities, key recreational areas for tourism, conservation land, plantations and farmland.

Aims

The aims of this project were to provide information on:

1. likely issues, effects and impacts of wilding conifers, based on their current geographical distribution and potential future spread.
2. the perception that wilding conifer spread increases the fire hazard over the vegetation types that they are replacing.

Objectives

The objectives of this project were to:

1) ***Define the geographical distribution of wildings in NZ high country***

- Describe the past (1990) and current (2012) spatial extent of wilding conifers within the New Zealand high country using existing spatial databases;
- Highlight the potential for increased wilding spread, including assessment of possible future extent based on trends in changing land use and spread from existing seed sources.

2) ***Describe the fire hazards associated with wildings and their control***

- Identify the key factors and issues influencing fire hazard in wildings, and define a methodology for determining fire hazard in wilding conifers;
- Identify appropriate models for estimating fire behaviour in wilding conifers;
- Quantify the fire hazards (biomass/fuel loads and fire behaviour potential) associated with wilding conifers relative to the fuel types they are replacing;

- Determine and quantify the impacts of wilding control methods on short and longer term fire hazard.

3) ***Transfer knowledge to practitioners to enable effective hazard management***

- Summarise and translate findings to rural fire managers through the provision of maps, a technical note and/or seminar that allows them to understand and apply this information when managing resulting fire hazards.

Key Results and Conclusions

Geographic distribution of wildings in NZ

The current spatial database has identified 321,756 ha of wilding infestation. Over the last 10 years, there has been a marked increase in area affected by wilding conifers, in the South Island especially.

Assuming that no control is undertaken, by 2020 the potential future wilding infested area could increase by an additional 150-160,000 ha. Generally the highest increase would occur in the South Island as there are less intense grazing regimes and more susceptible vegetation types available.

We noted that our results varied from estimates made by previous mapping exercises and expert knowledge. Further improvements could be made. In particular, validation of current wilding occurrences based on ground truthing or remote sensing techniques could improve the confidence in our results.

Fire hazards associated with wildings and their control

After reviewing the literature, we identified nine fire hazard stages and 44 potential fire behaviour models associated with wilding spread and control. The analysis reveals that over time, fuel characteristics change and in combination with weather conditions so too will fire behaviour.

Based on a hypothetical fire climate scenario, medium height scattered wildings would pose the most serious fire hazard (highest spread rates and intensities) across all the fire danger levels (low to extreme). During an extreme weather event, fire hazard for each of the various fuel stages showed a fair bit of variability amongst the current fire behaviour models indicating that further work is still needed.

Fire hazard in wilding conifers were shown to be dynamic, meaning that the fire weather conditions (Low to Extreme) as well as the stage of invasion or treatment had a strong effect on available fuel load, rate of spread, and intensity. This means that fire hazard will be affected by seasonal conditions, with differences between wet and dry seasons.

There are two recommendations to improve our knowledge on fire behaviour in wildings. 1) The development of new models from fire behaviour experiments or wildfire observations; or 2) modify existing models. In the short-term the reverse engineering of local or international models may offer the best solution until more comprehensive data sets are available.

Further research would provide fire managers and property developer’s with greater certainty on the potential impacts wilding spread and growth have on fire hazard and risk.

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July 2013

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1. Introduction and Background

What are wilding conifers?

"Wildings" is a term used in New Zealand for the unintended spread of introduced trees on the landscape. Many introduced conifer species (evergreen tree with cones) grow well in New Zealand and represents the major source of wilding invasions. Many introduced conifers can regenerate naturally, some more easily than others. The most common conifers found in New Zealand are (Froude, 2011 & Ledgard & Langer, 1999):

- Lodgepole Pine (*Pinus contorta*) – regarded as most vigorous spreader
- Scots Pine (*Pinus sylvestris*)
- Mountain Pine (*Pinus mugo*)
- Douglas-fir (*Pseudotsuga species*)
- Corsican Pine (*Pinus nigra*)
- European Larch (*Larix decidua*)
- Ponderosa Pine (*Pinus ponderosa*)
- Bishop Pine (*Pinus muricata*)
- Maritime Pine (*Pinus pinaster*)
- Radiata Pine (*Pinus radiata*) – most widely planted.

There are a number of conifer species that threaten New Zealand landscapes, mostly in the drier areas of New Zealand with low stature vegetation and light grazing. These unmanaged wildings are considered an invasive weed by many land owners and managers, and eradicating these weeds is difficult and expensive. Wilding spread occurs from various sources such as erosion control plantings, commercial plantations, shelterbelts and individual trees.

The problems associated with wildings

Historically, much of New Zealand was covered in native woody species, but today's drier landscapes are mostly treeless following Maori and then European settlement (due to fire, axe and grazing). New Zealand has an environment that favours woody growth (temperate climate, fertile soils and even rainfall distribution). Up until 40-50 years ago, these woody species would have been kept in check by burning, grazing and lack of seed sources (Ledgard & Langer, 1999).

Different land uses today and into the future will likely result in many parts of rural New Zealand experiencing an increasing cover of native and introduced woody vegetation. This especially is the case for wildings, as grazing pressure declines along with the numbers of farmed and wild animals, less vegetation is burnt (due to regulation pressures), and seed sources increase from plantations, woodlots and shelterbelts (Ledgard, 2004).

The natural regeneration of introduced conifers (wildings) has the potential to transform grassland and/or shrublands back into forests. This increased introduced tree cover is perceived as a threat to many values (conservation, tourism, pastoral and water).

The suggested problems associated with dense infestations of wildings are (Froude, 2011):

- changes in the landscape, especially disrupting open and treeless areas
- effects on visual values for tourism, by transforming scenic landscapes
- potential loss of biodiversity, by degrading habitats of native flora and fauna
- reduction in water supply in catchments

- loss of productivity in land use (i.e. grazing, farming)
- high control costs
- potential increase in fire risk.

Interestingly, conifers in the landscape can also be considered a benefit. Although the area of native forests has declined, the planting of introduced trees means that New Zealand is now a more forested land again. Plantations and wilding forests could be utilised for a range of benefits, such as:

- reducing runoff and erosion on previously degraded sites
- carbon capture and storage
- a renewable source for bio fuels (i.e. ethanol) and fire wood
- engineered wood products such as wood-plastic composites, wood-cement composites, cross-laminated wood plates
- recreational opportunities
- providing a refuge for native and exotic animals
- visually appealing to tourists
- visually appealing to homeowners
- nurse crop for native vegetation e.g.. beech trees.

Making economic returns from wildings has also been suggested through harvesting for wood/timber products. However wildings are rarely managed and are often of variable size, age and poor form. Hence, the commercial returns in this current climate are usually poor, with wood being sold as fire wood for as little as 50 cents to $2 a tonne (Ledgard, 2008). If international industries are processing lower quality wood and logs killed by beetles into new composite products[1] , then there is potential for using lower quality wood from wilding trees also. Despite the above positives, the general view about wilding forests is that they are largely held in a negative light.

How do wildings spread?

Many factors affect the distribution of wilding spread:

- presence and location of parent seed source
- direction and strength of wind
- vegetation type in neighbouring land
- grazing/browsing pressures
- presence of soil mycorrhizal fungi
- resistance to pests and disease
- climate
- land management
- timing of wind event relative to seed production/availability.

Considerable research has been undertaken to understand the invasion of wildings in New Zealand. Research to date includes modelling of the wind dispersion of seeds from trees (Buckley et al., 2005; Nathan et al., 2001), and the symbiosis with mycorrhizal fungi (Dickie et al., 2010), microsite conditions (Allen & Lee, 1989; Ledgard, 2002) and browsing pressure (Benecke, 1967). The agent for long-distant conifer spread in New Zealand is wind (Ledgard, 2001; Ledgard, 2004).

[1] Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings. June 10–11, 2008. Theme 8. Fibre Opportunities and Manufacturing. University of Northern British Columbia, Prince George, B.C. Pages 159-178.

The most vigorous spreading species are Lodgepole Pine, Corsican Pine, Larch and Douglas-fir due to their lightweight seeds. Depending on the specie, location and climate, wildings can produce cones at between eight and fifteen years of age, and produce vast quantities of seed that can be dispersed for distances of over 10 kilometres in favourable conditions (Ledgard, 2004). Seed will likely spread further if the sources are growing on ridgetops and slopes exposed to strong winds (take off sites). Wilding spread is largely predictable due to New Zealand's prevailing westerly winds, with invasions generally occurring to the east of the seed source (Ledgard, 2001). Wilding conifers are trees that self-establish from wind dispersed seeds and can be found growing either:

- as a dense stand, downwind and close to the parent source (fringe spread); or
- as scattered trees often at exposed sites far away from the seed source (distant spread of scattered outlier trees) (Figure 1); if left unattended these scattered trees can fill in and become dense.

Wilding succession or invasion occurs in a number of stages:

- Grassland with no wildings present
- Small scattered wildings present in open scrub or grassland (pioneer phase)
- Medium scattered wildings present in scrub or grassland, starting to fill in the gaps (transition phase)
- Large wildings present, closed forest canopy, tree crowns touching (forested phase).

Figure 1 Top: "fringe spread". The tree cover is usually dense where most of the seed falls. Bottom: "distant spread". The tree cover is usually scattered and trees can be found growing kilometres away from the parent source.

History of conifer spread in New Zealand

The seed sources for most of today's wildings are a result from forestry plantings (Froude, 2011) for:

- erosion control purposes (e.g. Kaweka Ranges, Marlborough's Branch/Leatham catchments and Mid Dome in Southland),
- research purposes (e.g. Craigeburn and Hanmer Forests in Canterbury and the Central North Island),
- timber production, shelterbelts and woodlots (e.g. Central North Island, and on private and pastoral lease land).

The historic spread of conifers in New Zealand's landscape is well documented by Ledgard, (2004). Conifers were first introduced to New Zealand in the early 1800's, and in the 1900's wildings were first recorded as an invasive weed spreading in the landscape (Ledgard, 2004). By 1960 the problem had become more apparent, especially in the Central Volcanic Plateau of the North Island and Mackenzie Basin in the South.

In recent years, efforts have been made to estimate the full extent of the area affected by wildings, which is currently estimated to be over 800,000 hectares in the South Island (North et al., 2007) and approximately 300,000 hectares in the North Island (Paul & Ledgard, 2011). The major areas of New Zealand affected by wilding spread are shown in Figure 2.

Today's extent of wilding affected areas is regarded as a different land matrix to that seen 10 years ago. This is a result of the recent increase in afforestation especially of Douglas-fir, and the increased control of wildings and major land use changes in the high country (e.g. tenure review). Such changes will impact the area of land that is affected by wildings currently and in the future, as seed source locations and surrounding land uses are creating new environments and changing circumstances for wilding spread and establishment.

The greatest concern for invasion is in the drier zones of the country and where there are areas of lightly vegetated or unimproved land with light or no grazing pressure. Wilding conifers are long-lived and can out-compete most open and relatively low stature plant communities. Interestingly, shade tolerant Douglas-fir appears to be infiltrating disturbed shrublands and forests more easily today than 20 years ago (Ledgard, 2002), probably due to the increased presence of symbiotic mycrorrhizal fungi. Conifers can also easily establish in disturbed areas (i.e. following fire) (Ledgard, 2004).

A major research priority highlighted for accurate monitoring and modelling of future conifer spread (species and density) is the development of a centrally managed spatial database (Froude, 2011). Such a database could also be used to determine estimates of fire behaviour (i.e. fuel loads and fire intensity) for past, current and future wilding areas.

Wilding control methods used

Every year a considerable amount of money is spent on managing wilding spread. Controlling wildings can be labour-intensive, difficult and expensive. However, if left unmanaged it is expected that wildings will spread exponentially to dominate tussock and scrub landscapes. A failure to remove wildings early on can also result in the costs escalating exponentially ('a stitch in time saves nine').

There are a number of techniques used in New Zealand, and details on these are found in two user-friendly handbooks (Ledgard, 2009; Ledgard & Langer, 1999). These guidelines emphasise the importance of removing wildings before they cone. The simplest way to determine what technique to employ is based on the size and density of the wildings present.

To implement the most cost-effective control technique, it is essential that a well thought out management plan is undertaken. A good management plan would identify: the history of spread leading to the current situation, the major factors that are influencing the spread rate, how fast this spread is occurring, the options for control (usually elimination, containment, or do nothing), and the estimated costs and priorities for such control (Ledgard, 2004). There is also a need for long-term commitment and funds where the area affected is significant.

Wilding control techniques in New Zealand include:

1. Burning
2. Grazing
3. Fertilising
4. Hand pulling of saplings
5. Hand tools (loppers, secateurs, axes, slashers, etc) for small trees
6. Power tools (i.e chainsaw or scrub-bar) to ring bark or cut large trees down
7. Heavy machinery (i.e. mulcher, digger/dozer)
8. Poisoning (foliar spray, cut stump, stem, root or bark applications)
9. Prevention by responsible planting techniques.

Control by grazing

In the past, grazing provided the most widespread and effective control. This control method is effective if the seedlings are less than one years old. It is more effective to combine grazing with pasture improvement (i.e. use of fertilisers) which allows for an increase in pasture grass competition. Grazing can reduce the spread of Radiata pine, Ponderosa pine and Lodgepole pine more so than that of Scots pine, Douglas fir and Corsican pine (Ledgard & Langer, 1999).

Physical removal

Physical removal of wildings is done by hand or using motorised tools such as scrub cutters and chainsaws. Hand pulling is for seedlings and the entire root system must be removed. Felling with an axe or chainsaw is used for saplings up to large trees. Wildings can be killed by felling as close to ground level as possible, making absolutely sure that all green foliage is removed. If any live foliage is left remaining, the tree will not die and continue to grow.

When done with helicopters (i.e. “skid hopping” from one wilding to another) to eradicate scattered populations, this technique can become a very costly exercise.

Chemical control

Considerable research has been undertaken to investigate mixtures of chemicals, desiccants and surfactants to kill conifer species (Ledgard, 2009). The success of effectively killing wildings depends on the species, climate, application method, and optimum concentration and mix of chemicals. The most commonly used is the non-selective chemical, diquat (Reglone). Other herbicides include glyphosate (Roundup), triclopyr (i.e. Grazon), picloram (found in Tordon and Grazon) and metsulfuron (i.e. Escort). Currently, a new “super brew” is in development as previous chemical rates and mixes have given variable results (Ledgard, 2009).

Chemicals can be applied to foliage, cut stumps, bark or roots either from the ground or the air. Aerial application by helicopter is becoming the more popular choice for both dense wilding stands (boom spraying) and especially when conifers are scattered across a large area (touch wand or nozzle gun application). Repeat sprays are often required to ensure killing of wildings. Currently, this is a costly exercise due to the price of chemicals, brew concentrations, flying costs and the area required to be sprayed. Vast quantities and repeat spraying of chemicals also have the potential to runoff and leach into drinking water and other aquatic ecosystems. They also have the potential to have significant non-target effects on desirable plants (usually native). The use of alternative methods (e.g. burning) instead of chemicals should be carefully considered around aquatic bodies.

Machinery

Heavy machinery such as mulchers and dozers can be used to remove dense areas of wildings. This technique can have adverse impacts of removing non-target plants and also allowing weed invasion. Dozers often pile trees into windrows leaving them to break down naturally or to be burnt.

Burning

New Zealand is currently lagging behind its international partners who use fire as a land management tool for a wide variety of applications, including fuel reduction and weed control. This practise used to be a common means of woody plant control, but today is infrequently carried out in New Zealand largely due to the loss of experience, liability issues, the cost of managing and suppressing a fire, and risks to neighbouring assets/values (Bayne et al., 2012). Fire has been used successfully in the past in combination with chemicals in the Central Plateau area (Bayne et al., 2012; Page et al., 2012).

There is renewed interest in using fire to remove areas of wildings in the South Island (Molesworth, Amuri Range, Mackenzie Basin and Mid Dome). This is because the use of fire could be cheaper, more effective at control and more environmentally friendly compared to chemicals. Experimental burn plans are being prepared to understand fire behaviour in wildings with and without chemical desiccation. Further research into monitoring post-burn regeneration and ecological impacts is also being formulated.

Internationally, fire is successfully used to control wildings (Kasel et al, 2005; Lindsay & Herpich, 2008; Richardson & Higgins, 1998). Seedlings and young pines can be killed by a low intensity fire, but a hot fire is required to kill mature trees (Kasel et al., 2005; Lindenmayer & McCarthy, 2001). The fire must be of high intensity to burn the majority of the canopy and bark of mature dense stands. There is the potential for seeds (stored in cones or buried in the ground) to be protected from a passing fire. If this occurs, it is likely that a follow up fire or chemical spray is required to remove any seedling germination. It also has been suggested that the use of fire could destroy non-target plants and create a seedbed for weed invasion (Ledgard, 2009). Rehabilitation (seeding of pasture or native grasses or woody species) of the site could be accelerated by landowners to prevent wilding re-invasion from neighbouring seed sources(Kasel et al, 2005).

Responsible planting

The spread of wildings can be minimised by managing current plantations and their planting design. Simple decision support systems and assessment methods have been developed to predict the risk of spread from existing sources (Ledgard & Langer, 1999; Paul, 2010; Ledgard, 2001). This can be done by:

- Avoiding planting trees on ridges and slopes exposed to the prevailing wind
- Removal of current trees on ridges (take-off sites) exposed to the prevailing wind
- Avoiding planting where vulnerable vegetation is located upwind
- Planting less spread-prone species on the margins of blocks (i.e. Radiata pine, or natives which could act as seed traps).

With whichever control method chosen, it is also important to implement restoration or rehabilitation programs at the site. This is especially required where lands are erosion prone.

An option is to sow seeds of natives (typically found growing locally e.g. beech trees or manuka scrub). A dead “nurse” cover from felled or standing trees can also provide shelter and improved growing environments for some natives. Even a sheltered forest environment of mature stands could allow the establishment of shade tolerant native species (Brockerhoff et al., 2003).

Fire hazard associated with wildings

Relatively little is known on the fire hazard posed by New Zealand wilding conifers. The widely held view is that wilding trees increase the fire hazard, and there are a number of instances where this may be the case, particularly where wilding spread is or has occurred in conjunction with residential development (e.g. Queenstown).

A wilding invasion present problems not only for land managers in controlling the spread of these wildings, but also has implications for fire fighters and fire managers. Wildfires in these areas could exhibit more extreme fire behaviour, are more difficult to suppress, and present greater threats to lives and property (Kaufmann et al., 2008). It has also been suggested that wilding control methods could increase the fire risk and threaten life and property in rural-urban communities, key recreational areas for tourism, conservation land, plantations and farmland.

Wilding tree spread is less likely in closed forest and scrubland canopies, or on improved mob-stocked pastures. However, wilding spread is likely to occur in lands that are lightly vegetated and lightly grazed, or if there is a natural disturbance (such as snow, wind or insect damage). The impact of wilding encroachment on fire risk and hazard is likely to change over time along with vegetation succession and the surrounding weather and topography.

NOTE:

Fire risk refers to the probability of a fire occurring; this is determined by weather and ignition source.

Fire hazard refers to the potential fire behaviour (spread and severity) once a fire has started, as determined by the vegetation type, arrangement, loading and condition of the fuels present.

(McPherson et al., 1990; Merrill & Alexander, 1987; NRFA, 1998).

Wilding fire hazard

The relative fire hazard associated with wilding conifers is dependent on a number of factors, including:

- The age and density of the wilding stand, which determine the fuel load, arrangement, condition (especially the amount of dead fuel) and spread potential;
- The wilding conifer species, which influences tree flammability (especially of live foliage) and stand structure, and therefore crown fire potential;
- The vegetation type being replaced, which determines the understorey that was/is present, and its contribution to flammability, fuel load and fire spread potential;

- The vegetation cover encouraged by wilding prevention and control techniques (e.g. standing dead trees, felled stems and slash, dense herbaceous swards);
- Fire weather and climatic conditions at the time of ignition;
- Topography of the affected areas.

Thus the relative fire hazard can be described by comparing the fuel loads, and potential spread rates and intensity of fires burning in wilding conifer stands with the fuel types (usually grasslands) that they are replacing.

A wildfire burning in surface fuels (i.e. grasslands) typically has reduced fire intensity and results in less excessive damage to vegetation and properties. Replacement of grasslands or scrublands into wilding conifer forests is likely to correspond to a shift from fast moving to slow moving surface fires (as wind is dampened in a forest environment and forest floors are generally more moist). However this can be offset by increased fuel loads associated with taller woody vegetation, so that flame heights and fire intensities are expected to increase also.

Areas of open scattered wildings would allow for warm dry microclimates, and would result in drier fuels compared to a closed forest. Open canopies allow the sun access to fuels, causing higher fuel temperatures. As a result, these areas are more likely to have a high ignition potential and experience high rates of spread and fire intensities compared to closed forests (Harrington, 1982). Where there is space between tree crowns the opportunity for a moving crown fire is low, but intermittent crowing (or torching) is very likely.

A wildfire would move through a closed forest with varying intensities or speed depending on the combination of weather and fuel conditions. In times of drought and extreme fire weather, fuel moisture content declines and results in more forest fuels being available to burn. When these conditions occur, a surface fire could spread faster and more easily transition into a crown fire. In windy conditions, the potential for spot fires would increase. In closed forests, the concentration of woody fuels would provide a tremendous heat source together with interconnecting crowns creating a hazardous potential for crown fire (Harrington, 1982).

Impacts of control on fire hazard

The impact of wilding control methods should also be considered a key part of any description of the fire risk and hazard associated with wilding spread. Control measures are likely to increase the amount of dead material and therefore the fuel loadings in areas, therefore presenting an even greater fire hazard compared to live wilding trees (the do nothing approach).

Increases in fuel loads (either as dead standing or felled trees on the ground, or as more grass or scrub cover) will result in an increased chance of ignition, greater potential for fire spread and higher fire intensity. The length of this increased flammability will depend on the amount of material left on the ground, the rate of decomposition, fuel moisture and other vegetation present. This expectation of extreme fire behaviour paired with higher flammable fuel conditions presents serious challenges to fire managers protecting the safety of fire-fighters and the public.

The effects of wilding spread and their control on fire behaviour have not been studied in New Zealand. However, we can look to the impacts of other natural hazards on forests that could provide likely insights. The effects of bark beetle outbreaks in the United States and

Canada could be a suitable substitute for wilding control. Forests invaded by bark beetle go through three distinct die-off stages: green, red and grey. During each phase, there is a change in potential fire behaviour due to the changes in needle chemical composition, foliar moisture content and available fuel loads. This was not largely understood until the 2012 fire season when wildfires burned through large areas of beetle killed forests in Colorado, USA (Hickey et al., 2012).

A closer look at the hazards associated with stages of chemical treatment of wildings can be loosely based on studies of forest insect attack. However, it must be recognised when comparing fire behaviour in conifer forests that experience insect outbreaks, that this does not result in 100% tree mortality (Schoennagel et al., 2012), which is the aim for land managers trying to control wilding pines. The different stages of forest mortality can be referred to as:

- Green stage (alive)
- Red stage (1-3 years)
- Grey stage (4-10 years)
- Old stage (10+ years).

Green stage
Fire risk and hazard is likely to be reduced during this stage. Mature stands of wilding conifers are relatively unlikely to burn except under the most extreme weather conditions. Stand age will affect predicted fire behaviour through the amount of fine fuel build up. In conifer forests, the amount of dead material available to burn is generally low and found mostly at the surface or elevated on lower branches. A closed canopy helps keep the forest floor cool and somewhat moist, as the canopy provides shade and reduces the amount of evaporation. As forests age, the amount of dead needles and branches building up on the ground increases which, when combined with extreme weather (i.e prolonged drought), increases the chance of a high intensity surface fire. Combined with low crown heights (compared to plantation forests), the chance of a crown fire developing in a mature wilding stand is much higher.

Red Stage
Following chemical treatment, a mature dense wilding forest that generally provided moist living fuels in the canopy and forest floor are now dead, dry, and falling, and have the potential to contribute to extreme fire behaviour. Within a year of chemical treatment, the green tree crown will fade to a yellow colour, and by the next year turn red. Time periods will vary with tree species. It can take up to two years for treated wildings to die off.

In the early stages of the red phase, needles die, turn red and dry out but persist on the trees for around two years. The total amount of biomass is relatively unchanged compared with the green forest; however the amount of available fuel is considerably higher. Foliar moisture is also now considerably lower and responds to changes in weather more easily. If the wilding forest is dense (over-stocked), this characteristic helps form a continuous vertical fuel profile that could result in a surface fire becoming a crown fire. If the tree density is low (i.e. scattered), crown fire may have difficultly occurring.

It is hypothesized that a crown fire could ignite and spread more easily in a red stage wilding stand, and have sustained fire propagation under less extreme fire weather conditions. These forests are usually more flammable than live forests and therefore are associated with extreme fire behaviour (Alexander & Stam, 2003). Extreme fire behaviour expected would include: candling, torching and crown fires even under mild burning conditions, and an increased potential for area ignition (mass fire). This type of fire environment should raise serious concerns for firefighters and their safety (Alexander & Stam, 2003).

Grey Stage
By this stage, there is little fine fuel remaining in the canopy to support a crown fire and the trees now appear "grey". Needles are falling to the forest floor, and now provide fuel for a ground or surface fire. Crown fire hazard is hypothesized to be reduced compared to the green and red stages. Due to the loss of canopy fuels, the probability of active crown fire is expected to be lower or nil.

Once trees have fallen, large concentrations of woody fuels would now increase surface fire intensities and make for difficult fire suppression. As time progresses, needles are less flammable (less volatile) and along with downed woody material, are likely to be in a later stage of decomposition. At this time, these surface fuels may have higher moisture contents and be more punky (with a lower heat of combustion), so that fire intensities and flame lengths are less than they could be at the end of the red stage.

A more open canopy now provides less shade and an increase in wind speeds are experienced within the stand. These factors promote drier surface fuels and increase the amount of fuel available to burn (Pollet & Omi, 2002). There is also the likelihood of the presence of grasses, scrub or young wildings growing through the fallen or standing dead trees. These fuels are likely to increase the surface flame heights.

On the other hand, open forests are also more exposed to rainfall and humidity and any live vegetation would not have to compete for water from dead trees – all of which could impact on the flammability.

Old Stage
During this stage, there is the matter of high surface fuel loads when the limbs and stems fall down. These higher surface fuel loads can result in greater intensities and prolonged mopping up. Just how long the dead confiers will remain standing will vary depending on weather conditions and decomposition rates. Fire hazard is likely to change from a slow moving fire in a green forested area, to a fast moving grass fire amongst downed or dead standing wildings. Schroeder and Mooney (2012) suggest that the concern for potential extreme fire behaviour is less in the grey phase compared to the red. However, there is the potential for dead trees to create major fuel loads and shedding of bark could increase spot fire occurrences.

There is also the likelihood of the presence of other vegetation (grass, scrub and new wildings) growing beneath any remaining standing dead trees and through downed stems/branches. The growth of grass fuel types is likely to be enhanced when wildings are felled and remnant dead trees lie on the ground. In a simple pilot trial, both native and exotic grasses were found to increase in ground cover and height (Paul & Ledgard, 2008). The presence of dead trees also appeared to help the growth of some woody natives as well (Paul & Ledgard, 2008).

The high fuel loadings of large woody material would contribute to high and long lasting heat loads especially when combined with other lighter vegetation present. In combination with dead light flashy fuels (grasses), head fires will likely spread rapidly compared to healthy forests. Falling snags (tree branches or stems) will also pose serious risks to fire fighters mopping up on the fire line especially during strong winds and after the passage of the fire front (Alexander & Stam, 2003).

Fire hazard associated with insect damage

Currently, there is a growing body of research investigating the impacts of bark beetle or spruce budworm epidemics on fire risk and hazard. It is suggested that insect invasions into forests cause widespread mortality and significant changes to stand structure, composition and fuel loads. Of the studies reviewed, mixed results were found. Of note though, is that although fuel condition plays an important role in fires, the effects of weather and topography should not be underestimated and may account for the variable results found in the published literature.

Simulated or modelled experiments

There is a stark difference in the number of published simulated experiments compared to experimental burns. Simulated studies were the preferred choice as experimental burns can be risky due and impacts on assets and public safety should one escape.

One study looked into the concern that a bark beetle outbreak would increase the probability of active crown fire by producing high loads of surface and canopy dead fuels (Simard et al., 2011). After modelling potential fire behaviour, Simmard et al., (2011) found that the outbreaks may reduce crown fire behaviour. They showed through simulation that the potential for crown fires decreased from the green to grey stage. Simard et al., (2011) suggest that beetle outbreaks may reduce the probability of crown fire in the short term by thinning pine canopies.

Schoennagel et al., (2012) modelled potential fire behaviour across the three stages of insect attack. They found that canopy fuel moisture was lower in the red and grey stages compared to the non-attacked green stage. This resulted in the potential for crown fire to occur at lower wind speeds and less extreme fire danger conditions. Surface fire intensities were also significantly increased in the grey and old stages. Schoennagel et al., (2012) suggest that the risk (probability) of crown fires is elevated in insect attacked forest but the overall fire hazard (crown fire potential) is similar across all three insect-impact stages.

Page and Jenkins (2007c) suggest that drastic changes in fire behaviour will occur in insect attacked forests. Based on custom-made fuel models, increases in rates of surface fire spread, fire intensities and crown fire potential were predicted in the red (current epidemic) and grey (post epidemic) stages. They suggest that increases in surface fire behaviour are a result of greater wind speed effects in grey forests and fine fuel loading in the red forests.

Jenkins et al., (2008) undertook a study to understand the effects bark beetles had on fuel accumulation and subsequent fire hazard. Fuel samples were collected from endemic (handful of trees), epidemic (widespread) and post-epidemic (5 years after) stands of various tree species. Their results showed that a change in fuels over time creates periods for high intensity or severe fires. Early in epidemics there is a net increase in the amount of surface fuels compared to the endemic stage. In the post-epidemic stage, large dead fuels and live surface fuels dominated. They also suggest with their fire behaviour predictions that for surface fires, rate of spread and intensities were higher in the current epidemic stands than in the endemic stands. Tree torching was more likely in post-epidemic stands but crown fires were less likely due to decreased aerial fuel continuity.

Klutsch et al., (2011) undertook modelling experiments in beetle infested forests and show that healthy forests that have continuous canopies are expected to have a greater potential for crown fire than in insect damaged forests. This was mirrored by several studies that predicted a high probability of crown fire during the red stage (Hoffman, 2011; Page & Jenkins, 2007b). The risk of torching was no different between a healthy forest and insect damaged stands in Klutsch et al., (2011). They also discovered that insect infested forests with and without tree fall had greater surface fire flame lengths, fire intensity and rates of spread.

Laboratory studies

Experimental laboratory studies have shown that foliar moisture content has a profound effect on flammability and ease of ignition in forest stands (Alexander & Cruz, 2012; Jolly et al., 2012; Page et al., 2012). Lower moisture contents (i.e. increased flammability) during the red stage were shown to increase the ease of ignition, reduce the time to ignite, required lower temperatures for the fuels to reach ignition point, and produced greater intensity compared to green foliage (Page et al., 2012).

Jolly et al., (2012) investigated the moisture content, chemical composition and time to ignition from needle samples off green (healthy, un-attacked), recently attacked and red (dead) trees. They found that foliar moisture content was significantly different between the three stages. Red needles had the lowest fuel moisture content. Ignition time also varied significantly with green needles taking the longest time to ignite. Their results show that a loss in moisture content and changes in chemistry increase the flammability of insect attacked trees. They suggest less heat would be required to ignite the foliage of attacked trees and crown fire potential will be higher in attacked stands that retain dead foliage.

Williamson et al., (2011) conducted single tree ignition tests in beetle killed lodgepole pines. They found that under late winter/early spring conditions, green healthy crowns were not receptive to fire. In contrast, red needled crowns were more receptive to fire, with the period of increased risk lasting for about two years. They also found that crown fire involvement (torching) was inhibited after a significant loss of needles. This suggests that a sparse canopy in insect attacked stands may help explain why crown fire does not occur for some experimental burns.

Field-based studies

Page and Jenkins (2007a) examined the effects of insect attack on ground, surface and aerial fuels during and after an epidemic. They found that there were statistically significant increases in the amounts of fine surface fuels in early stages of attack (red stage). Results also showed that there were large increases in the amounts of dead woody fuels and regeneration of other vegetation was greater in post epidemic stages (old stage).

Experimental burns in insect damaged forests in Canada showed that fire behaviour was significantly higher when tree mortality was greatest (Stocks, 1987). Spring fires were observed to be much more severe with continuous crowning, high spread rates and downwind spotting.

Schroeder and Mooney (2012) conducted experimental fires on treated (simulated insect damage) and untreated stands over a range of FWI values to determine threshold differences in crown fire initiation, rate of spread and fire type. Their findings suggest that low foliar moisture content in treated stands results in greater crown involvement. There was no difference in fire rates of spread or FWI thresholds for crown involvement. However, they did observe greater crown involvement in the treated stands. Schroeder and Mooney (2012) observed a noticeable amount of needle loss in the treated stands and suggest that this could inhibit crown fire initiation and crown rates of spread. They also observed a lack of transpiration in the treated stands that caused the duff layer to increase in moisture, but in turn didn’t have an effect on surface fuel moisture content.

Wildfire observations

There appears to be a limited number of actual wildfire behaviour observations documented in insect attacked forests. Documenting wildfires and fire behaviour provide much needed proof to test the accuracy of fire behaviour models. The few reports on wildfires are a surprise and could likely be due to the fact that such observations do exist but have not been made publicly available. The few observations from fire managers in Canada and USA report that fire behaviour exceeds their expectations for insect attacked forests.

In western Montana in 1961, one of the largest wildfires occurred in the region. It was reported that forest fuel accumulation following 30 years of beetle attack greatly increased the difficulty of controlling the wildfire (Jenkins et al., 2012; Roe et al, 1971).

Fire behaviour observed by personnel in British Columbia indicates that fires spread faster and at higher intensity in red needle stands compared to green stands. Fire personnel also reported higher ignition probability from long range flying embers Schroeder and Mooney (2012). They suggest that crown fire initiation happened more readily and rates of spread were greater in the red stage, when dead trees contained flammable needles Schroeder and Mooney (2012).

Summary

In summary, there is a growing body of research on the effects that insect damage has on forest fuels and fire behaviour. A recent detailed review compared and contrasted 39 studies (Hickey et al., 2012a; Hickey et al., 2012b). This review of published literature found that fuels change over time with insect damage. However the review highlights that there is still a huge gap in the understanding of fire behaviour in these forests. Hickey and his team suggest a number of likely explanations for differences among the current published literature:

- Looking at the effects of one or two drivers and not combinations of multiple drivers;
- Not looking at the fire environment as a whole, and not including the effects that weather and topography have on fire behaviour, in addition to fuels;
- Looking only at extreme weather and not less extreme (i.e. early season and lower wind speeds);
- Some look at certain stages (green attacked, red or grey) but do not make comparisons with un-attacked stands;
- Not all conifer forests are the same - different tree species are likely to have different fuel characteristics;
- Stand characteristics - forests attacked by insects don't suffer 100% mortality, there is often mixing of various stages of health;
- Stand mortality - some forests that are red attacked could have 40% mortality, compared to other studies that had 80% mortality; this affects fuel structure and conditions within the stand.

Current published literature on beetle killed forests therefore could provide an indication of the potential risks and hazards for dying and dead wilding pines. However, researchers and fire managers must apply these theories with caution to wilding conifers Hickey et al. (2012a); and Simard et al. (2011) point out that there is huge variability within insect killed stands. This results in variations of foliar moisture contents and fuel amounts in the canopy, which in turn creates variations in actual fire behaviour. Stand structure and fuel characteristics in insect damaged forests are likely to be very different to the treatments used to control wilding forests. With the aim of 100% mortality in wilding forests, more fuel is likely to be available to burn and fire managers could potentially expect an even greater fire hazard.

Fire behaviour associated with wildings

Much less is known about fuel loads, fire intensities and rate of spread in wilding conifer stands; however, fire behaviour in New Zealand grasslands, and to a lesser extent shrublands, have been extensively studied and are reasonably well understood (Pearce & Anderson, 2008).

> ***NOTE:***
>
> ***Fire behaviour*** depends on the interaction of multiple factors: weather, topography and fuel characteristics. A fire's behaviour varies with changes in weather, terrain, fuel amounts, fuel arrangement, and fuel moisture.
>
> Fire managers are primarily interested in how fast a fire moves (rate of spread), how hot it burns (intensity), torching (passive crown fire), crowning (active crown fire), fire whirls, spotting (extreme fire behaviour), and smoke production.

The only published study for New Zealand to date is a wildfire case study describing the fire behaviour observed during the 2008 Mt Cook Station Fire in the Mackenzie Basin (Clifford & Pearce, 2009; Scion, 2009).. This wildfire spread through a stand of wilding trees into surrounding grasslands, burning a total area of 756 ha. Fuels in the fire area were predominately wilding conifers (Corsican pine and Larch) of various ages and density, interspersed with scattered patches of scrub (matagouri), tussock and bracken fern.

Areas of dense wilding conifers had high available fuel loads that contributed to extreme fire behaviour (high fire intensities, large flame lengths, crown fire runs and spotting). In contrast, areas on the landscape that had variability in fuel continuity and structure also contributed to comparatively slow spread rates, which were considerably lower than those predicted by available forest fuel models (for immature and mature pine plantations, from Pearce & Anderson , 2008; Clifford & Pearce, 2009).

Relevant fire behaviour models

A key finding from the Mt Cook wildfire case study (Clifford & Pearce, 2009) was that the current New Zealand fire behaviour models for plantation forests (mainly of Radiata pine, from Pearce & Anderson (2008)) are not applicable to wilding fuels, and that work is required to identify or develop more accurate models. This presents serious problems to fire managers responsible for developing suppression strategies during fires in these wilding fuel types.

The Canadian Fire Behaviour Prediction System (FCFDG, 1992), on which the New Zealand models are based, includes several other natural forest models that may be more appropriate to wilding conifers. These include models for mature and immature Lodgepole pine, and uneven-aged Ponderosa pine-Douglas-fir stands that include Larch or Lodgepole pine and understorey conifer thickets. Similarly, the U.S. 'Behave' fire behaviour prediction system includes a number of natural forest fuel models that may also better represent wilding fuels (Scott & Burgan, 2005).

A list of models that could be suitable or calibrated to predict fire behaviour in New Zealand wildings is reviewed in section 3.2. These have been separated out based on the size and density categories indentified by (Ledgard, 2009):

Size:

- Small trees (less than 2 cm diameter at the base; and less than 0.5 m tall);
- Medium trees (range between 2 – 20 cm diameter measured at 1.4 m high; and taller than 1 m);
- Larger trees (greater than 20 cm diameter measured at 1.4 m high; and taller than 10 m).

Density:

- Scattered; or
- Dense (forest often has a closed canopy, or trees will have touching crowns).

The models presented in section 3.2 were selected based on the stand structure and fuel conditions, particularly for the fuel layer carrying the fire, instead of just representing a particular species (FCFDG, 1992, Pearce & Anderson, 2008). Fuel types in the Canadian FBP System in particular are described qualitatively, rather than quantitatively, using terms describing stand structure and composition, surface and ladder fuels, and the forest floor cover and organic (duff) layer (FCFDG, 1992). In the case of stand structure and composition, stand density is described in terms of overstory stocking and crown closure (after FCFDG, 1992) as either:

- open (crown closure is incomplete, although overstory clumping may be significant);
- moderately well-stocked (crown closure is incomplete or variable with season);
- fully-stocked (complete crown closure); or dense.

Other stand structure features of importance to fire spread and crowning may also be classified, including overstory species composition, stand height, height to live crown, live crown length or crown ratio, stand maturity, or horizontal and vertical continuity.

If the suggested models do not accurately represent fire behaviour in wildings, the models could be customised using same technique described by Jenkins (2012); and Jenkins et al., (2011). Jenkins and his team developed custom U.S. fuel models following fuel characteristic measurements and using the methods developed by Burgan and Rothermel (1984). They were then able to predicted potential fire behaviour (rate of spread, flame length, intensity and potential for crowning) using the (Rothermel, 1983) fire spread model and BEHAVE plus[2]. Hickey et al. (2012b) highlight that most models assume canopy fuels are alive so that foliar moisture contents are not representative for killed trees. This may need to be looked at closer for any custom made models for wilding conifers.

[2] *BehavePlus* is a Windows software application to predict wildland fire behaviour for fire management purposes. It is a collection of models that describe fire behaviour, fire effects, and the fire environment. Downloaded from: http://www.firemodels.org/index.php/behaveplussoftware/behaveplus-downloads

2. Wilding Conifer spread

As early as the beginning of the 20th century the self-establishment of exotic conifer seedlings in New Zealand was recognised (Smith, 1903) and in the 1940s and upsurge of self-establishing wilding conifers outside plantation stands was reported. Beauchamp (1962) documented such spread for the Mackenzie Basin for conifer species like *Pinus ponderosa*, *Pinus nigra*, *Larix decidua* and *Pseudotsuga menziesii* (Hunter and Douglas, 1984). At the turn of the 21st century wilding conifers were seen as a wider and greater problem that required more attention and management. The spread of wilding conifers was increasingly recognised as a threat to biodiversity, landscape values, hydrological effects and pastoral productivity. The weed potential of some conifers species, especially *Pinus contorta,* was realised (Benecke, 1967). However the full extent of all infestations was never quantified or mapped during the early period of invasion.

In the last 10-15 years, major efforts have been made to document and quantify the extent of wilding conifers in New Zealand, especially those on high country pastoral lands. Initial approaches to document the wilding extent were dominated by sketching affected areas on maps and recording descriptions of locations that were stocked or “affected” by wilding conifers (Ledgard 2003 provides a long list of such reports). Increasingly, such maps were digitised to be used in Geographic Information Systems (GIS) and regional spatial libraries for management purposes. Newer approaches aim to directly map wilding areas directly through a mapping GIS interface with GPS (Global Positioning System) capabilities.

Other wilding conifer mapping approaches have included expert knowledge and interpretation to define land areas that are affected or where certain values like biodiversity are at risk from wilding conifers. For example, DoC uses the following definition: “area likely to be affected within 15 years if no control is undertaken” (Department of Conservation, 2001). In 2007 spatial information on wilding conifers in the South Island was combined to provide an island-wide estimate of affected areas (North et al., 2007).Expert knowledge was used to standardise and re-define areas and infestation status. Unfortunately the mapping exercise was never fully completed. However, it provided a more standardised estimate of wilding affected areas for the whole South Island.

Because of the very different approaches for how land management agencies have approached the quantification of areas, and the variety of definitions used for “affected area”, an overall estimate of wilding affected area and the quantification of the degree of infestation has not been available for the country as a whole, or for individual regions.

Mapping exercises based on surveys and inventories or through remote sensing approaches (aerial photograph or satellite image interpretation or processing) have been used to estimate the area of various land cover and use categories (Land Cover/Use DataBase) or areas for specific vegetation types (Anon, 2011; Dymond et al., 2012). As mapping accuracy is an important necessity to gain confidence about area estimates and their interpretation, associated inventories or “ground-truthing” should be a vital part of mapping exercises as Dunningham et al. (2001) and Brockerhoff et al. (2008) showed. Mapping accuracy declines rapidly with objects that are hard to detect or do not provide good spectral differentiations. Wildings conifers are certainly in this category as they are often not the dominant vegetation type.

Independently to the ground-truthing approach, stand-alone plot based inventories have been used to estimate and describe the extent and demographics of forests in many countries. This approach can provide estimates with a calculated accuracy and precision if the sample is unbiased (Tomppo, 2000; Tabacchi et al., 2005). As current estimates are based on mapping exercises with unknown accuracy (e.g. where do you draw the line between affected and unaffected areas?; what are the criteria to include or exclude a parcel or area?), a systematic 1 ha plot based inventory across currently identified areas was chosen in this study to estimate areas affected based on defined criteria.

The modelling of wind dispersed seeds has progressed strongly in recent years. Based on intense and localised studies, models have been developed that incorporate wind characteristics, demographics of species, and the spatial position of seeding trees in the landscape. This approach results in very sophisticated models which require high information input to explain occurring patterns of seed spread in the landscape (Bohrer et al., 2008, Nathan et al., 2011, Caplat et al., 2012b). Such models have also been simplified and linked to step-wise process models to predict invasive fronts and development of infestations (Buckley et al., 2005, Caplat et al., 2012a). A much simpler method based on an Expert Knowledge Decision Support System (DSS) has been developed by Ledgard (2008) and is accepted and used as a tool for assessing the wilding risk in many locations in New Zealand (Rachel Fyffe, Ministry for the Environment, pers.comm.). The DSS was translated in 2010 into a simple static geospatial model which was then further improved using a statistical approach to estimate the probabilistic density of the wind-directed spread with generalising assumptions to reduce the need for additional data (Schibalski and Paul, 2010). This simple model was used in this report to predict the extent of further infestations across New Zealand from initial known wilding areas.

2.1 Design and setup of a national wilding database

A spatial database was designed in Access 2007 that dynamically links to spatial data-layers under ARCGIS 10. This was undertaken to capture the dynamic changes in wilding affected areas that can occur over time. Existing datasets from previous efforts to map the extent of wilding conifers (such as Ledgard (2004) and North & Ledgard (2007)) were sourced and, where necessary, translated into compatible data-formats.

In order to consistently map the current extent of wilding affected areas, land management agencies known to be involved in wilding conifer management were contacted to provide relevant spatial data. In this initial stage, only the provided extent in the form of polygons (area and point) is currently used as data standards on collecting weed and pest information are highly variable between agencies and by region. Once collection and assessment standards are better defined and data collected according to such standards, the use of additional information provided by the multitude of providers will be possible.

Datasets received were transformed to a standard raster-format with a common origin and a minimum resolution of 1 ha (100m X 100m pixel). Areas smaller than 1 ha or linear in shape (shelterbelts) were also included in this process by assigning 1 ha pixels. This was undertaken to avoid the loss of such small areas in the process. Overlapping areas (as a result of adjacency between land authorities), mapping inaccuracies and changes in mapped boundaries over time were identified. The most appropriate datasets linked to these identified areas (e.g. the best datasets in terms of additional information and date of mapping) were assigned for later analysis.

A standard data protocol for the database and the associated inventory approach (spatial analysis) was developed to characterise a national standard for wilding affected areas. Aerial photograph interpretation plots were used in the next phases to gather the following information in the table over leaf.

Table 1: Parameters required for a national wilding database.

Database field	Type	Field Format
Dominant wilding species group	4 classes; nominal scale	Text
Co-dominant wilding species	4 classes; nominal scale	Text
Density class	6 cover classes; ordinal scale	Text
Frequency	counts < 100 trees/ha; metric	Long integer
Development stage	4 classes; ordinal	Text
Aggregation type	6 classes; nominal	Text
Spread evidence	2 classes, nominal	Text
Dominant vegetation type	4 classes; nominal	Text
Dominant vegetation cover	10 classes; ordinal	Long integer
Control evidence present	3 classes, nominal	Text

Current and future wilding spread

The first objective is to provide an estimate of the area currently affected by wilding conifers, and an accuracy of this estimate based on a national imagery plot approach. Secondly, using the survey data to model predictions of future wilding area based on the current situation and the spread from these known locations.

To estimate the current wilding affected area, we based our survey on available GIS datalayers from land management agencies which have mapped out areas where wildings would be expected or wilding control was carried out or planned. We used the total mapping extent as our inventory area, in which we place our assessment plots in a systematic fashion.

Areas with purposely seeded or planted spread-prone conifer species have been excluded, except for areas that are unmanaged in a forestry context (many erosion plantings from the late 1970's-80's). Commercially managed plantations, shelterbelts and woodlots as part of a managed farm have been excluded as these are not wilding conifers by definition, but rather landscape components that can contain spread-prone species. "Wilding affected areas" are defined as areas that have at least one visible wilding per hectare. In the current survey this means that such a wilding would have been identifiable on the aerial photograph used (depending on resolution and quality of the image).

The survey is restricted to areas identified by land agencies as areas affected by wilding conifers. Nearly all local land management agencies delegated to assess and manage invasive species have carried out simple mapping exercises to identify and locate areas affected by invasive alien plant species. Datasets based on such mapping exercises are variable in terms of demographic data and area mapping accuracy and do not follow a common standard that allows the comparison between maps and data for various regions.

Therefore we simply used the extent of the datasets and layers given by the agencies and used a standardised approach across all the areas. In the first instance we collated the available and currently valid digital maps and spatial datasets from land agencies, and the areas provided were themselves not adjusted or modified in extent, but rather combined and then assessed in terms of the severity of the invasion in these areas using 1 ha imagery plots placed systematically across the total area. Data was requested and received from the following land agencies (Table 2).

All other land agencies (e.g. Marlborough, Tasman, Otago) were not able to supply spatial data on the extent of wilding conifer affected areas (except those areas included in the DoC layers for the specific region).

To complement the datasets from the land authorities (Table 2), the 2007 spatial database of wilding spread areas (areas were wildings were found) collated by North et al. (2007) and were added to extend our survey area. The re-survey of these previously identified areas during a pre-screening exercise revealed additional areas, especially in the South Island. These additional areas were added to the dataset and surveyed accordingly. However, some areas were not in the dataset as they were not supplied by land authorities and not in the 2007 database. These were areas located in the Richmond Range in Nelson, the Marlborough Sounds and areas in the Hawkes Bay (non-DoC areas).

Table 2: Datasets of wilding affected land received from land management agencies.

Agency	Date	Type of dataset/form of provision
Department of Conservation (DoC)	Multiple dates (2006 to 2011)	GIS layers; Area of control or intended control for wilding conifers
Land Information New Zealand (LINZ)	2011	GIS layers of control areas
Hawkes Bay	2011	Hand drawn maps and locations
Horizon	2010	Identified area with wildings present
Queenstown Lakes District Council (QLDC)	2010	GIS layers of wilding affected areas
Southland		No GIS information available (except DoC's)
Canterbury	2010	GIS layers of affected areas and where wildings or spread species present
Bay of Plenty	2010	GIS layers of affected areas and where wildings or spread species present

Data handling

All areas provided were rasterized to a resolution of 1 ha (pixel resolution of 100m x 100m) using ARCGIS 10.1. Areas smaller than 1 ha or linear in shape (often shelterbelts) were also included in this process by assigning 1 ha pixels, avoiding the loss of such small areas in the process. Areas were rasterized based on a common raster-frame with a random starting point (Top 6210000; Bottom 4720000; Left 1020000; Right 2100000; NZGD_2000 Transverse Mercator).

The use of a raster algorithm allowed the removal of slivers and artificial areas as a result of overlapping layers and to maintain the full extent of the area. The created rasters were merged to produce a full national coverage. Overlapping pixels (mapped by multiple authorities or at multiple times) were simplified to retain only the latest most informative pixel information through a spatial merging process carried out in ARCGIS 10.1.

Survey design

A stratified grid sampling approach was used for placing survey sample plots in the area of interest. Using such an approach allows the even placing of sample plots across large areas (good coverage) and using random sampling theory for analysing inventory data as the grid is randomly placed over the area of interest (random starting point and direction).

To improve the efficiency of the sampling two different sampling intensities (grid sizes) were used. Larger polygons were covered with a larger grid of 4.5 km mesh-size. Smaller polygons not intersected by this grid were sampled with a 1.5 km grid. Both grids had the same origin and orientation (imposed into each other). A weighting was applied depending on the grid-size for any calculations of national averages. Fifty-one polygons out of a total of 852 polygons were sampled by randomly chosen grid-points as neither of the grids provided enough or too many sample points in these polygons to be efficient.

Aerial imagery

The availability of suitable high spatial resolution imagery covering the two main islands of New Zealand is still limited and most imagery available has been captured over a number of years. The most up to date, nearly full coverage aerial imagery was supplied by Terralink Ltd. and used in this survey. The time period of acquisition ranged from 2004-2011. Over 50% of all sample plots were surveyed over imagery taken during the 2006-2011 period, with one third of these plots surveyed on imagery taken in the 2011 season. Spatial resolution was for all imagery in the sub-meter range dominantly 0.75-0.4m. For the North Island nearly all survey plots were interpreted from aerial imagery taken in 2008 and later. South Island imagery is older with most survey plots surveyed on aerial imagery taken between 2004 and 2010, predominantly with 2006 - 2008 imagery. In some instances (e.g. Branch – Leatham), GoogleEarth imagery was used as aerial imagery was not available or of poor quality and age.

Sample plot assessment

A data protocol was developed for the assessment of survey sample plots to characterise a national standard for wilding affected areas. On aerial photograph interpretation, plots of one hectare were located and the following information collected.

Dominant and co-dominant wilding species (if present) were recorded under the following categories:

- Pine
- Douglas-fir
- Larch
- unknown
- none

Rather than using a species level, our approach was based on distinguishable groups of species containing one or many species to simplify interpretation and reduce interpretation error. On the national level, the simple grouping approach should provide enough information regarding the mix of species that are spreading, especially as pines have a tendency to spread into grasslands and Douglas-fir (more shade-tolerant) is able to invade shrublands (Davis et al., 2011).

Wilding density within a plot is described using six distinguishable cover classes:

- very sparse < 5% plot area cover,
- sparse <15% plot area cover,
- moderate <30% plot area cover,
- dense < 50% plot area cover,
- very dense <75% plot area cover,;
- closed >75% plot area cover.

We used the simple density/cover classes to estimate the "severity" of wilding conifers on a per hectare level (plot). In addition we used a count method up to a threshold of 100 individuals to estimate the wilding numbers that "create" the density, providing a better picture of infestation level (see below, e.g. very sparse cover but a high number of individuals versus sparse cover created by 5 large individuals).

Stems per hectare:

- Tree count per hectare (plot) up to 100 tree,
- Fully stocked plots with more than 100 trees.

Development stage of wildings is described in four classes:

- ***Not visible***, too young and small to see (so no visual landscape impact and not detectable if present. Surrounding wildings however indicate that plot will contain wildings (this class was not used later for any statistical calculations);
- ***Young just visible*** in high resolution imagery and at a smaller size, probable age of up to 5-10 years;
- ***Mature clearly visible*** and probably of an age between 10-20 years, reached coning age;
- ***Old clearly visible and tall***, probably above 20 years of age, well coning and wider seed spread due to height;
- ***Mix*** refers to a multi-development and age situation, were a clear categorisation in the above classes could not be achieved.

We are aware that the link between size and form of trees and their physiological age is not strong for wilding conifers as environmental conditions and external factors can strongly influence this. However it provides a starting point for interpretation of the potential cone production and spread risk from these wilding trees.

Aggregation provides a description of spread stage and the spatial distribution of wildings:

- ***Unknown*** - no clear pattern is recognised;
- ***Clustered*** - grouping of trees through close germination to parent trees;
- ***Outliers*** - single trees without any closer neighbours in the proximity;
- ***Open spread*** - a loose shotgun pattern with scattered trees in proximity;
- ***Dense spread*** - a close pattern with close by trees (trees start to dominate vegetation picture).

The aggregation classification provides an indication of the progress and establishment situations that can occur during the infestation of a site.

Spread evidence provides a description of the current spread situation:

- ***Fringe*** - establishment of younger trees close to a parent tree, often dense;
- ***Wave*** - more distant and wider dispersed wildings, indicating a wider spread event especially if trees are of similar age;

- ***No spread evidence*** - no wave or fringe pattern evident.

Similar to the aggregation description, spread evidence can be used for interpreting the stage of infestation and whether wildings spread vigorously in terms of short distance, medium or long distance spread.

Dominant vegetation type for the 1 ha plot was also recorded to describe the vegetation wildings were found in, with eight types:

- Native forest
- Plantation
- Wilding forest
- Shrubland
- Tall grassland (Tussock)
- Low producing grassland
- High productive grassland
- Bare ground

The relative cover of the vegetation type was also recorded in 10% steps.

Where control evidence was found in a plot, this was also recorded by describing the control type as felled or standing dead (through spraying or stem poisoning).

Statistical analysis

Simple binomial calculations, based on extent surveyed and the number of plots, allow the estimation of wilding affected areas in the total area provided by the land management agencies, together with associated uncertainties about this estimate.

Area of any strata $\bar{y}_i$ can be calculated by

[1] $$\bar{y}_i = \frac{x_i}{x_{all}} \times total\ area$$

where x_i is number of plots for stratum *i* and x_{all} the total number of plots surveyed.

The associated SE (standard error, probability) is calculated by

[2] $$SE\ (P) = \sqrt{\frac{x_i}{x_{all}} \times \left(1 - \frac{x_i}{x_{all}}\right) / x_{all}}$$

Calculations were carried out separately for each grid size and added together to account for the different weight that various grid-sizes provide.

More detailed quantitative and semi-quantitative inventory data was also calculated as mean per hectare. To account for the different grid sampling intensities we used the following formula:

[3] $$\bar{y} = \frac{\sum_i \bar{y}_i A_i}{\sum_i A_i}$$

with $\bar{y}_i$ is the mean of the variable of interest in strata *i* with the associated area A_i.

The associated variance for each inventory variable can be calculated by

[4] $$V(\bar{y}) = \frac{1}{A^2} \times \sum_i A_i^2 V(\bar{y}_i) + \frac{1}{A^4} \sum_i \bar{y}_i^2 \left[A_i^2 \sum_{j \neq i} V(A_j) + V(A_i) \left(\sum_{j \neq i} A_j \right)^2 \right]$$

Collected data on wilding demographics allows us to describe the population and provide estimates of certain key factors with the associated uncertainty around this information.
In this survey, an area of 1.47 M hectares from a total of 1.57 M ha (i.e. 93%) has been surveyed based on our grid based plot sampling. For the remaining unsurveyed area no grid point fell into the provided polygon areas, which were in most cases very small.

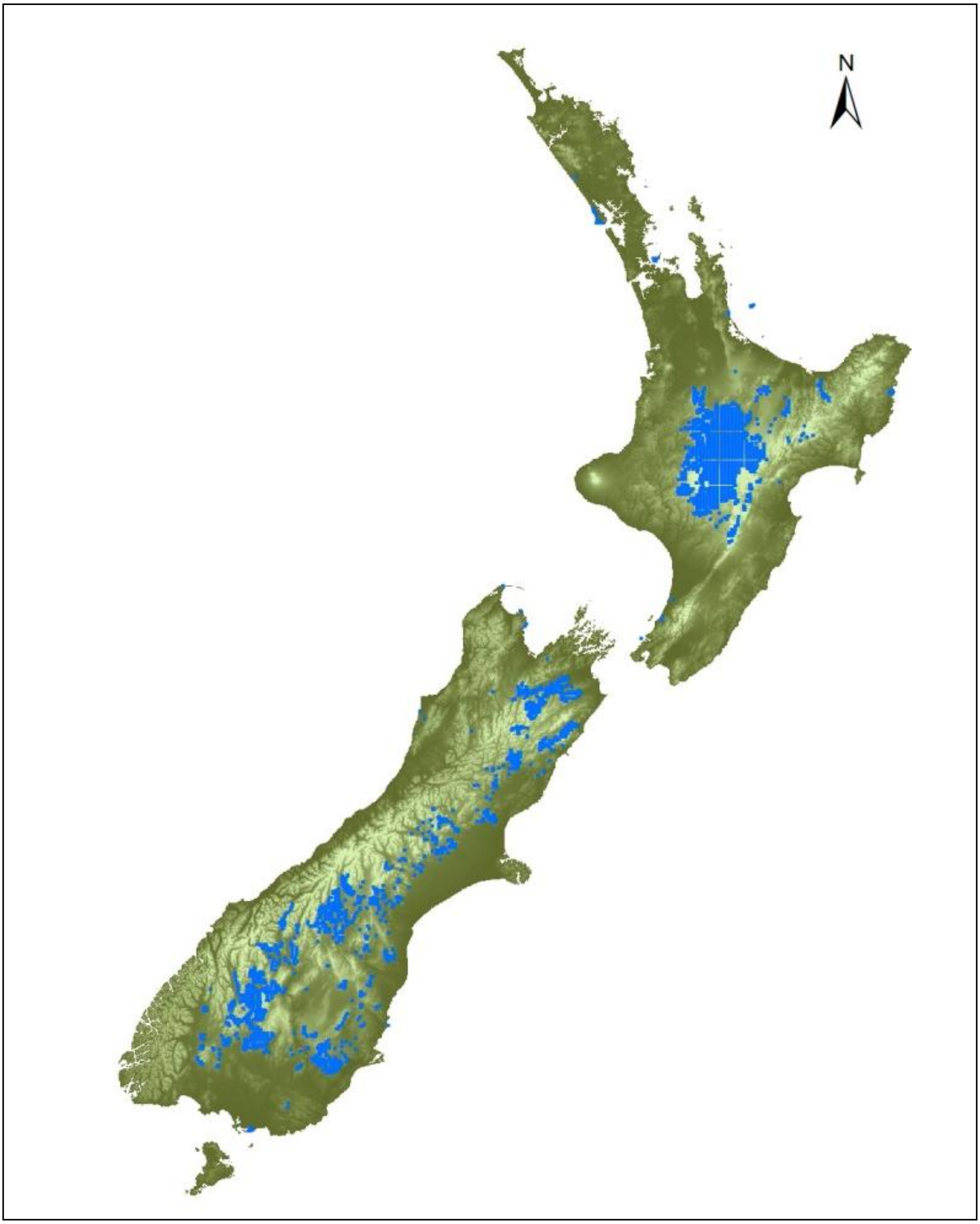
Description of the inventory

A total of 1.47 M hectares were surveyed covering the largest wilding areas identified by previous studies. 103,875 ha in 18419 identified polygons with a mean area of 5.63 ha were excluded as no grid intersection fell into these polygons (half of these polygons were ≤ 1 ha). Shelterbelts, small woodlots and plantation forests make up the dominant land-cover of these polygons.

In total, 2377 one ha imagery plots were used with 1474 plots sampled on the 1.5km grid representing 688 polygons provided by land management agencies, 615 plots on the 4.5 km grid representing 114 polygons, and 288 plots based on a position on both grids (random) representing 51 polygons.

The spatial distribution of the total surveyed area is shown in Map 1. Some areas with known wilding populations are not present as no maps and spatial information of the wilding extent and affected area were available. Main areas with a lack of such information were the Marlborough Sounds, some parts of the Hawkes Bay and parts of the southern North Island. High country regions and areas with a known wilding history are well represented.

Map 1: Areas used for the wilding inventory and covered by the sample grids.



2.2 Wilding spread modelling

One aim of the inventory assessments was to collate input data suitable for use in a spread model to predict the potential future extent of wilding affected areas. As different sampling intensities were applied, the representative area of a wilding plot inside a polygon varied (e.g. plots sampled on the 4.5 km grid represented a surrounding area of 2025 ha, whereas plots on the 1.5 km grid represent an area of 225 ha). Twenty dispersal points were randomly spatially distributed into an area according to the grid size around the identified wilding plot. As a further simplification, only randomly chosen dispersal points located in areas able to carry wildings were selected (urban, water, exotic plantation forest and native forest were excluded). We used the newest Land-Cover/Use Spatial DataBase available (LCDB3) as a mask to exclude any points placed in the land-use classes mentioned above.

To model spread from these dispersal points, we used a generalised model for wind dispersal of wilding conifer seed based on earlier work of Ledgard (2008) and Schibalski and Paul (2010). The model runs were carried out under the following generalising assumptions:

The dominant wind direction, during the seed release period is a north-westerly across the South Island and westerly direction in the North Island. A Gaussian distribution of wind directions is assumed with 135° (for the South Island) as a mean (μ) and a standard deviation of 20 (σ, model parameter). The probability value is standardised through dividing by the maximum value resulting in values between 0 and 1. Thus a high value (≈ 1.0) stands for a high risk of seed dispersal into that cell relative to the direction of the seed source. These directional values are later multiplied with the probability for dispersal distance and can be interpreted as a weighting factor (reducing that second probability unless = 1.0). Figure 2 shows the probability density function as described above, illustrating the highest values for south easterly direction (around 135°) downwind in South Island conditions.

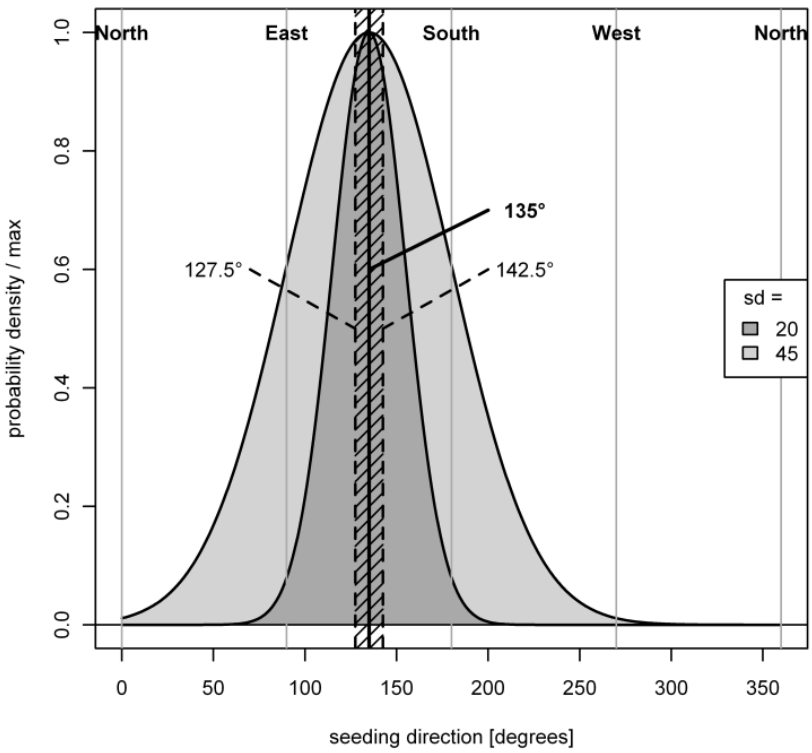


Figure 2*:* Dispersal direction probability factor. Derived from standardised Gaussian distribution with mean seeding direction of (μ) = 135° and standard deviation (sd), of seeding direction set to either 20 or 45.

Seed terminal velocity for all wilding species was assumed to be the same and therefore seed dispersal distance was treated the same for all species. To describe the dependent dispersal distance in the model a Gaussian distribution was used (Okubo and Levin, 1989). The distance distribution can be described by two parameters, mean and shape (sd). The only sensible value for the mean in this case is zero (no negative distances). While the mean specifies at which distance the distribution has its maximum (closest to the seed source in the case of seed dispersal), the value for the standard deviation (sd) determines how quickly the curve declines with increasing distance from the seed source. The smaller the value for sd the steeper the decline of the curve and, thus, the shorter the dispersal distances (or rather, the less probable are long dispersal distances). The use of different standard deviations is shown in figure 3. Values for sd can be used to differentiate between species, i.e. higher values (= fatter tails) for species with longer dispersal distances.

We modelled spread distance with a mean of 0 and shape (sd) of 1.75 for all plots assuming that wilding plots represent species with the ability to disperse seed over long distances ("having fat seeding tails") such as Douglas-fir (*P. menziesii*) and Lodgepole pine (*P. contorta*). These species have a low seed-wing loading (Ledgard 1990), resulting in widespread seed dispersal compared to other species like Ponderosa pine (*P. ponderosa*). No differences in seed release height were made between tree stages or plots and no differences in exposure or wind speed assumed for specific sites.

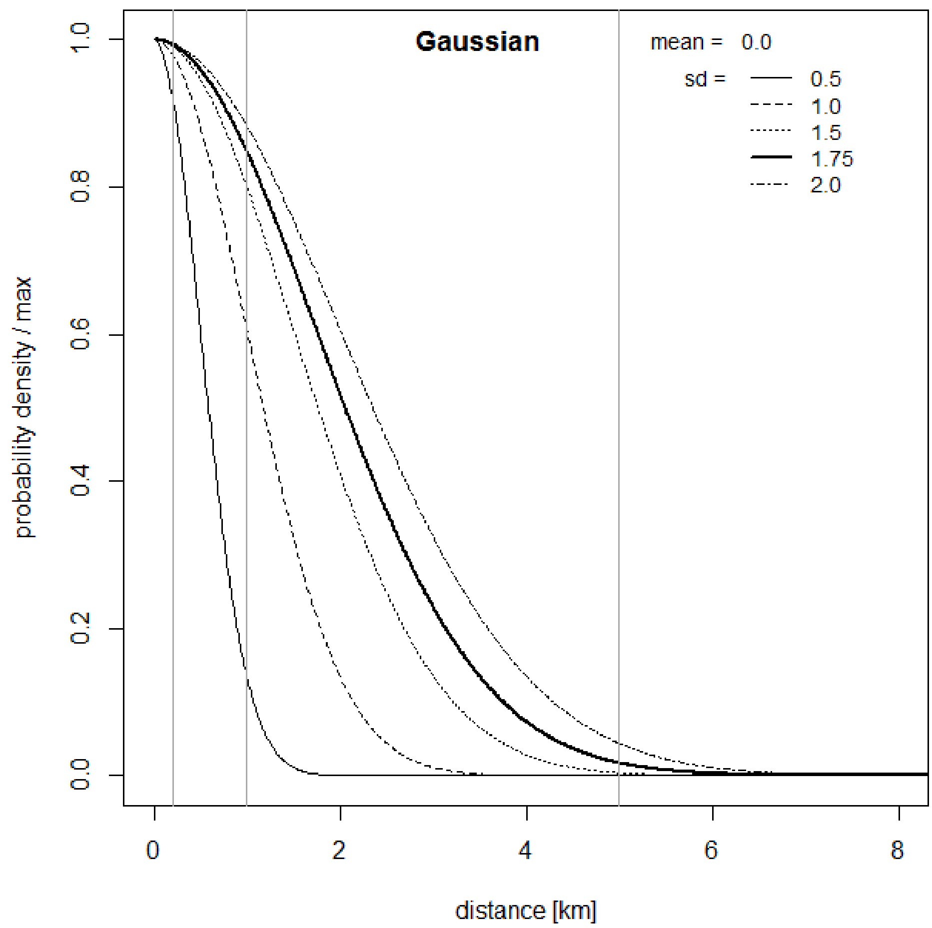


Figure 3: Gaussian distribution with different shapes (sd) describing the dispersal kernel. The used mean = 0 and shape (sd) = 1.75 results in a mean close to the source but accounts for long distance spread through the "fat tail".

Model scenarios

The inventory provides information about the status and development of wildings, e.g. their development stage. Two scenarios were therefore run differentiated by the use of known wilding presence (plots) and their development stage:

Scenario 1: Only dispersal kernels were used that currently could be characterised as seed producers, identified by the plot information available. No differentiation between species was made and the same dispersion ability was assumed.

Scenario 2: All dispersal kernels with wildings of any age were used extending the expected dispersion over a wider timeframe. Again no differentiation between species was made and no additional areas were used as dispersal kernels (e.g. earlier affected areas from older trees).

The results of the spread modelling are expressed as a probability density for areas surrounded by known wilding conifer areas. Potential area increase through wilding spread was calculated by summing up areas with a probability density of 0.005 or more to provide an estimate including long distance spread (LDS) up to 5 km (Figure 3) and 0.03 to provide an estimate for shorter distance spread (SDS) of up two 2 km aligned with the DSS developed by (Ledgard, 2008). We assumed that in areas with even lower probability density the establishment of wildings is very unlikely and infestation risk is low, because propagule pressure, in our case the intensity and frequency of seed rain from existing wildings, will be very low and will not support wilding establishment in these areas.

2.3 Current and Future wilding extent

Current distribution of wildings

The current spatial database created has identified approximately 1.3 million hectares of land that is infested by wilding conifers. The total area includes areas that still require control or where control has already been carried out. The latter however does not mean that these areas will be wilding free as re-invasion is possible or complete eradication is not yet achieved, as this can require multiple control events.

A preliminary analysis of the wilding areas identified (Figure 4) shows that:

- nearly 45% of all identified wilding areas are one hectare in size or smaller. This size category includes many shelterbelts that contain spreading conifer species;
- 25% of the identified affected areas are 1 - 4 ha in size;
- approx 15% of the area is 4 -16 ha in size;
- approx 10% of the area identified is between 16 - 256 ha in size; and
- approx 5% is between 256 - 65,536 ha in size.

The distribution of wilding affected areas is shown in map 2. As expected, the most-affected areas are located in the central North Island (volcanic plateau), central Otago (Queenstown basin), the Mackenzie basin, inland Marlborough and Southland, and Canterbury high country.

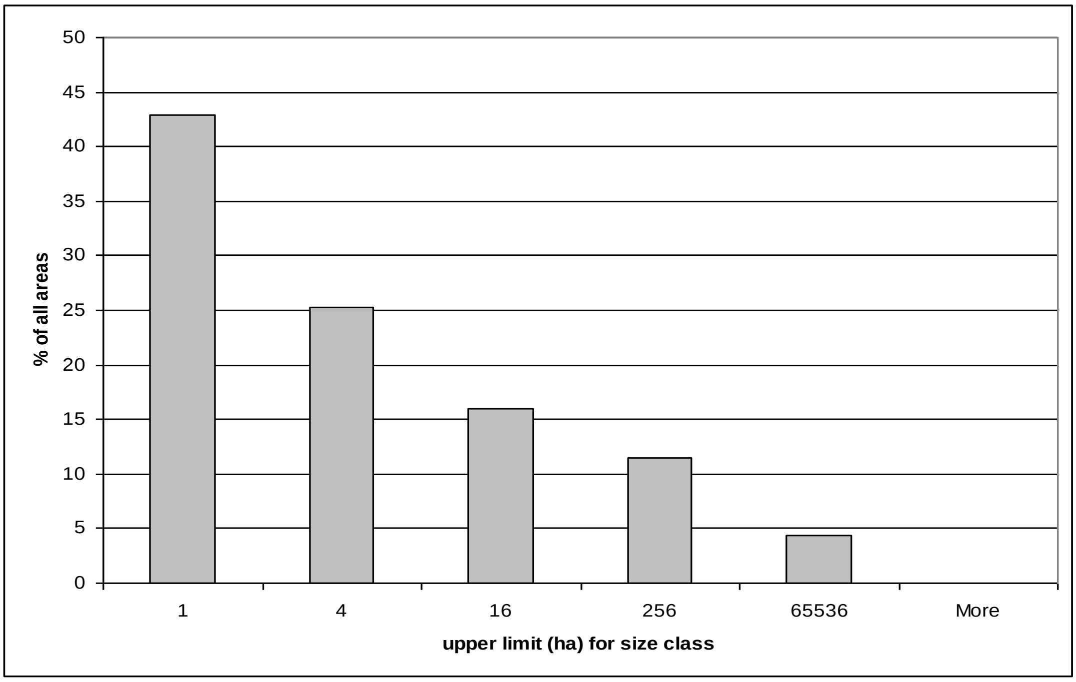
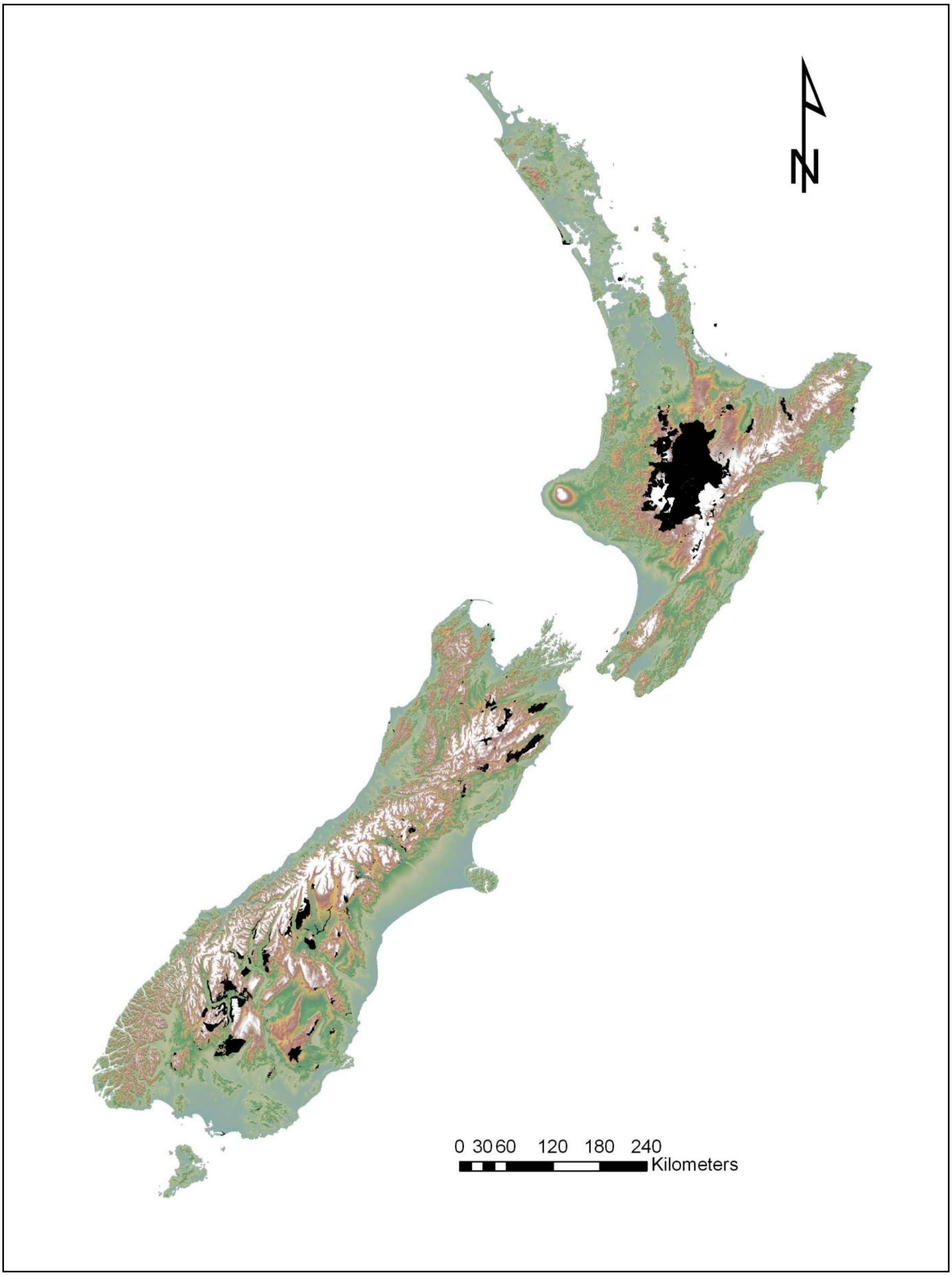


Figure 4: Frequency distribution of all individual wilding affected areas collated based on size (log scale).

Map 2: Distribution of wilding affected areas (black areas) in New Zealand, based on data provided by relevant land agencies.



Based on a systematic 1 ha aerial imagery sample plot inventory covering a total of 1.47 M hectares using 2377 plots, the current wilding affected area is estimated as 321,756 ha with a probable limit of error (PLE) of 10.5% (± 33,858 ha). In other words, wilding conifers were found on 22% of the surveyed 1.47 M ha. The likely actual area with wildings (at least one wilding per hectare) will therefore be between 287,897 and 355,614 ha (95% Confidence Interval). Area estimates are collated in Table 4.

In the South Island there has been a marked increase in area under wilding conifers over the last 10 years. In the North Island we estimated that around 75,000 hectares are affected by wildings today, which is half the area (150,000 ha) estimated in 2001 Ledgard (2003).

Very dense infestations, where wilding conifers form forests and reach full coverage are estimated to currently cover 16,668 ha with a PLE of 33.5%. The likely actual area of such wilding forests will therefore be between 11,088 and 22,248 ha (95% CI).

The largest single vegetation type affected by wildings are grasslands with 182,204 ha (CI ± 26,753 ha), followed by shrublands with 81,098 ha (CI ±18976 ha), and other land (includes bare areas and open native forest) with 41,786 ha (CI ±14524 ha).

Plantations and shelterbelts feature in the surveyed area with 212,553 ha and 34,838 ha respectively, totalling 17% of the area surveyed. The remaining survey area not affected by wilding conifers and not stocked with plantations and shelterbelts is 843,501 hectares (CI ±41,061 ha), or 57% of the surveyed area.

Table 3: Estimated areas of wilding affected and unaffected vegetation types in New Zealand.

Predominant vegetation type	*Affected areas in ha (± 95% CI)*	*Not affected - included plantations and shelterbelts. (± 95% CI)*
Grassland	182,204 (± 26,752)	394,728 (± 38,225)
Shrubland	81,098 (± 18,976)	200,384 (± 29,693)
Wilding forest	16,668 (± 5,580)	---
Other landcover/uses	41,789 (± 14,524)	303.096 (± 35,157)
Plantation[3]	--	212,553 (± 27,309)
Shelterbelts[1]	--	34,838 (± 13,103)
Total	321,756 (± 33,858)	1,145,781 (± 33,858)

By using the current area estimates and comparing them with earlier estimates of wilding affected area (Hunter and Douglas 1984, Ledgard 2003, North et al. 2007), we can indicate trends over time (Figure 5). Our current estimates show an increase in wilding affected area which has accelerated over the last 10 years, and shows a very steep increase from 50,000 ha to 200,000 ha for the South Island. In the North Island the area estimated today is approximately 75,000 ha smaller than in 2001 when it was estimated to be 150,000[4]. As the North Island land agencies have been very active in controlling wildings (esp. in the CNI), such a decline of wilding affected areas under the definitions used is likely. Many areas

[3] *Plantation and shelterbelt trees were not treated as wildings as trees in this vegetation types are managed.*
[4] *See the discussion how the different estimates have been derived and what definitions where used at the time.*

might now be wilding free or have a much lower density of wildings present that is detectable remotely.

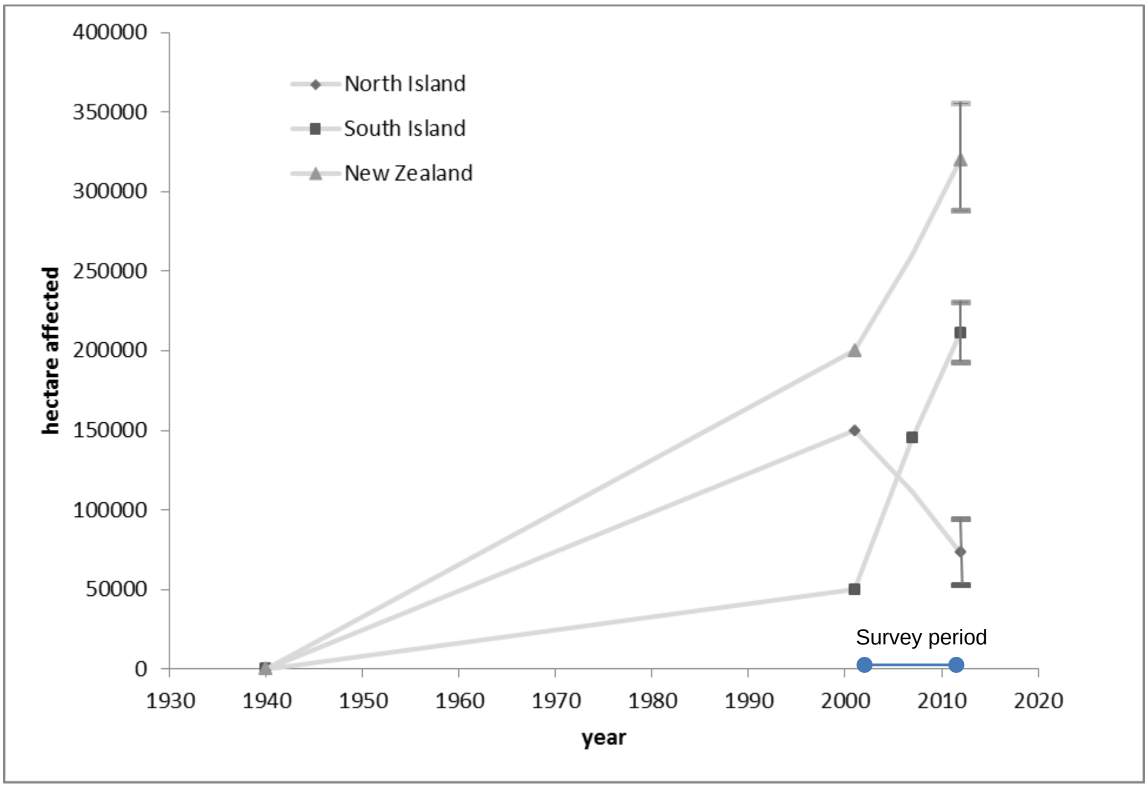


Figure 5: Change of wilding affected areas over time based on previous estimates and current inventory. Past data taken from Ledgard (2001), Ledgard (2003) and North et al. (2007) and given references. 2012 data is given as averages and 95% Confidence Intervals of inventory estimates.

Demographics

Wilding affected areas are still dominated by pine species with 48.8% of plots stocked with pine species (*Pinus contorta*, *Pinus nigra* and other *Pinus* species). For 43% of the wilding affected plots, no clear species distinction was possible. Just over 6% of the wilding affected area is stocked with Douglas-fir (*Pseudotsuga menziesii*) wildings, and only in 1.5% of the area Larch (*Larix* spp.) was present as the dominant wilding species.

The age structure of wildings in the surveyed affected sites shows that most areas carry wildings of younger ages, as 65% of the plots had wildings classified as "young" with a probable age of less than 5 years (this includes plots categorised with pines not clearly visible)[5]. 15% of the plots were classified as mature wilding plots and 16% with various ages. Old trees were only found in 1.2% of all plots containing wildings.

The wilding affected areas are composed of:

- 44,303 ha that have a high infestation with over 100 wilding trees per hectare,
- 184,576 ha with a mean stocking of 18 trees per hectare and
- 92,876 ha where tree numbers could not be clearly determined.

[5] *Plots were classified as wildings not visible, particularly when younger trees were found in close vicinity, but not identifiable in the plot itself (due to pixel resolution or shrubs present which complicated the count).*

The analysis of the density cover data indicates that:

- More than 37% of the affected area is very sparsely infested by wilding conifers. In these areas the wildings do not reach more than 5% cover on a site.
- At 19% of the sites, wildings reach slightly more cover (up to 15%) and are sparsely distributed.
- 15% of the plots had moderate to dense infestation levels (under 50% cover).
- In nearly 10% of the plots, the infestation was very severe with over 50% wilding cover on the infested areas.
- In 19% of the plots, it was not possible to carry out a density assessment, mainly due to problems in identifying the wilding cover.

In 137 plots (21%), the present wildings showed a clustered appearance that can be associated with fringe spread around outliers. Outliers lacking visible fringe spread were found in 13% of wilding plots. Open spread of wildings was most common (30% of the wilding plots), indicating a distant or more open fringe spread from a seed source. Dense spread where "infilling" occurs or the seed rain appeared to be heavy was found in 13% of all wilding plots. Again, in approximately 21% of the wilding plots, an assessment of wilding aggregation type was not possible.

Future distribution of wildings

Based on our modelling the potential future wilding infested area will increase by 157,597 ha over the next 8 years, based on a maximum spread distance of 5 km from known currently seeding wildings. By including only short and medium distance spread up to 2,5km the results will be more likely 102,352 ha.

Using all current wilding plots we estimated a new infested area of 540,506 ha when including long distance spread, more than a doubling of the current extent of wilding infested areas. The predicted increase in the North Island was only a tenth (48,411 ha) of that in the South Island (492,095 ha), which has a far higher potential for wilding establishment as more suitable land areas are present.

Hotspots of spread were visually identified as: Mackenzie Basin west of Tekapo; the Remarkables and their surrounding areas near Queenstown; areas west of Hanmer Springs, Craigieburn Range and the Kaikoura Ranges in the South Island; and in the North Island the Kaimanawas, Ruahines and areas along the Napier-Taupo Highway as well as Mount Tarawera in the Bay of Plenty.

The modelling results are presented for the two scenarios outlined in the method section, each with two variations. A timeframe of eight years (up to 2020) was assumed for the modelled spread process, as most species start seeding and coning at age eight and older (Ledgard 1996). Figure 6 shows the possible increases from the current estimates.

Scenario 1: For the first scenario, using only plots with currently seeding wildings and long distance spread of up to 5 km from a seed source; the area that could be infested in the near future is predicted to increase by 157,597 ha by 2020.

Assuming only short and medium distance spread up to 2.5km through currently occurring seed rain from established wilding conifers, 102,352 ha will be infested in the near future.

The potential newly infested wilding area in the North Island could be 5,412 ha, far smaller in size compared with the South Island where 152,185 ha is predicted under a long distance spread scenario.

Under the short and medium distance spread scenario, the resulting area would increase in the North Island by 3,299 ha, again significantly smaller than in the South Island which has an estimated increase of 99,053 ha.

Scenario 2: For scenario two, with all current wilding plots used (as opposed to just those old enough to seed) and long distance spread was assumed, the modelling resulted in a new infested area of 540,506 ha by 2020. The current wilding extent would therefore nearly triple by 2020.

The predicted increase in the North Island was only a tenth (48,411 ha) of that in the South Island area (492,095 ha), which has a far higher potential for wilding establishment as more suitable land areas are present.

However for the North Island, this would still result in nearly doubling the current affected areas, and for the South Island, the increase would be more than 1.3 times the current area.

Under the short distance spread variation, the potential increase would be less severe totalling 371,113 ha by 2020; 34,771 ha in the North Island and 336,342 ha in the South Island.

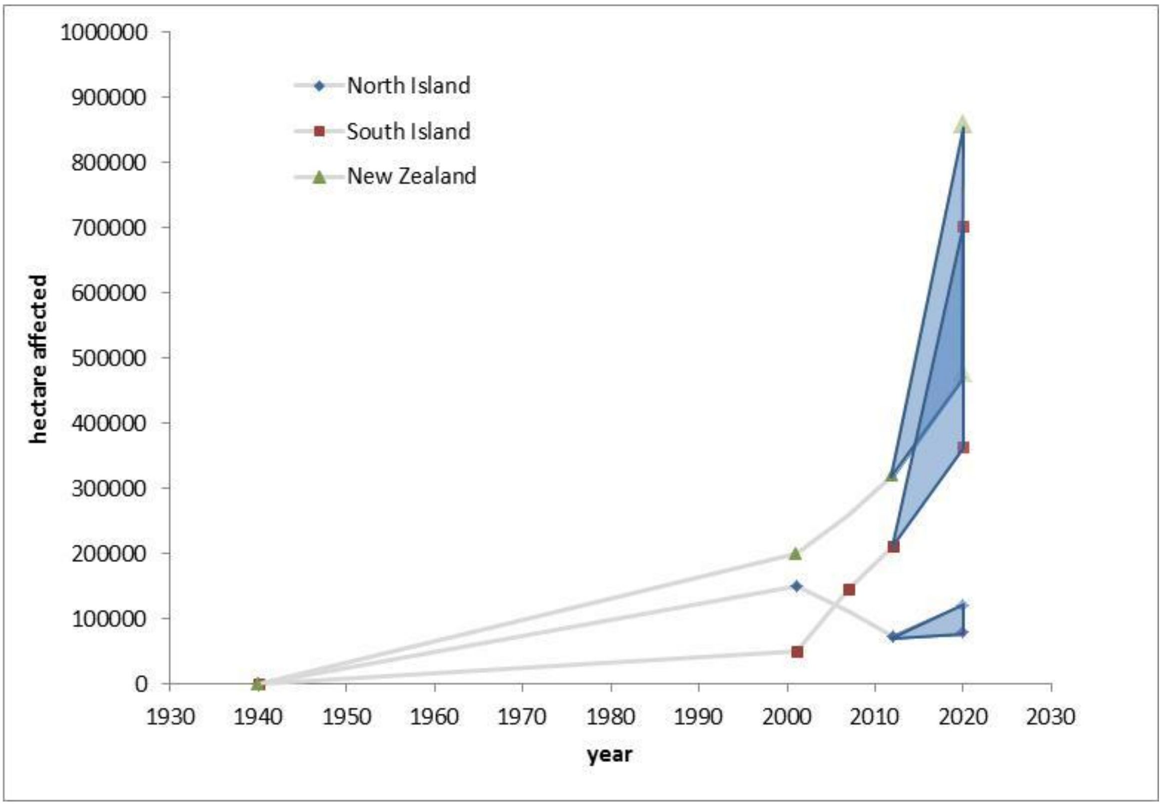


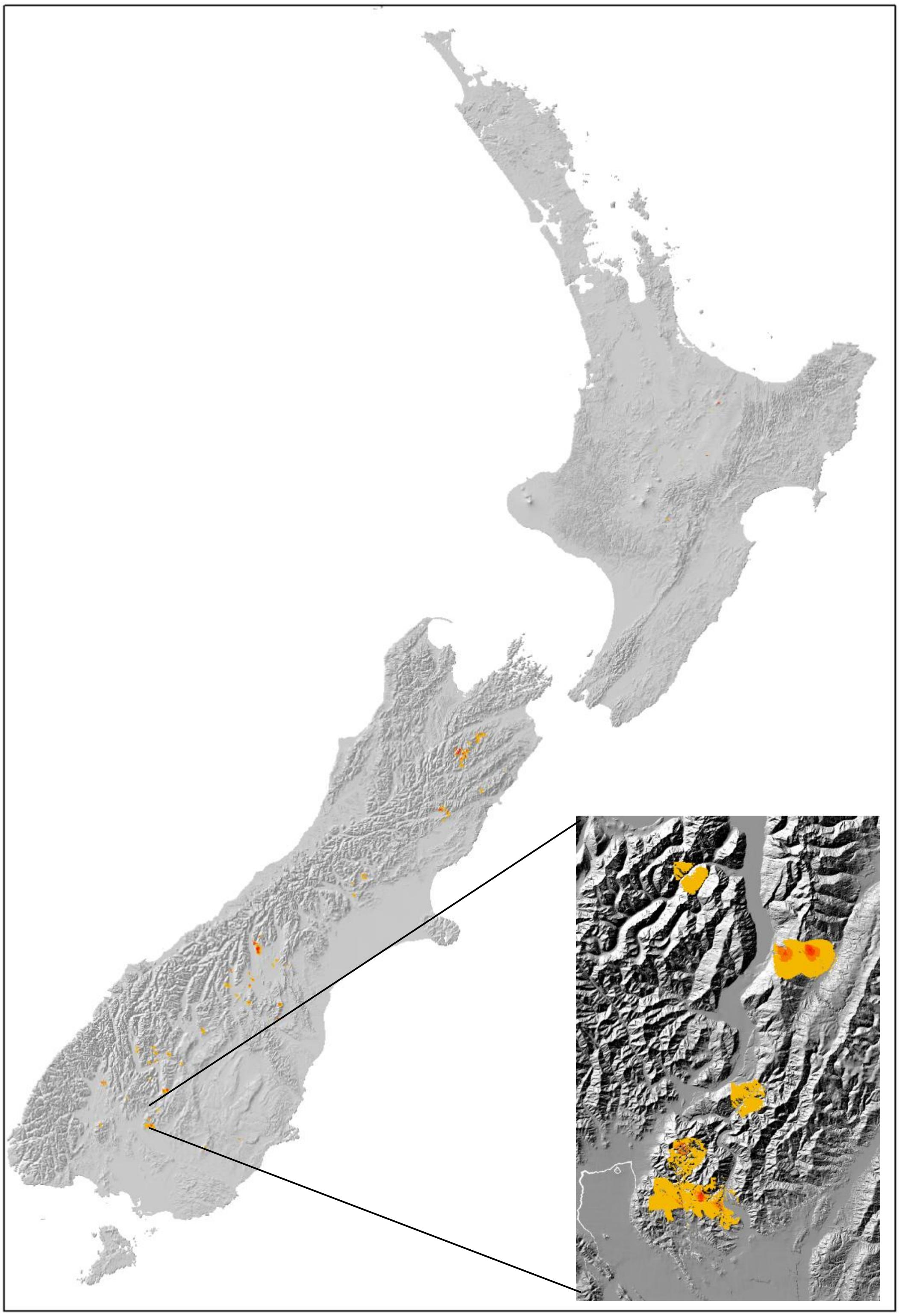
Figure 6: Estimated potential expansion of wilding affected area in total, and for the South and North Islands separately. Maximum and minimum predicted values are shown based on the two modeling scenarios with known current seed sources (lower bound) and all known wildings (upper bound).

Using eight years as a timeframe (up to 2020) the first wave of infestation would result in a predicted total affected area of 540,506 to 860,506 ha if no management and control are undertaken. The highest increase would occur in the South Island as more suitable sites (less intense grazing regimes and more susceptible vegetation types) are available.

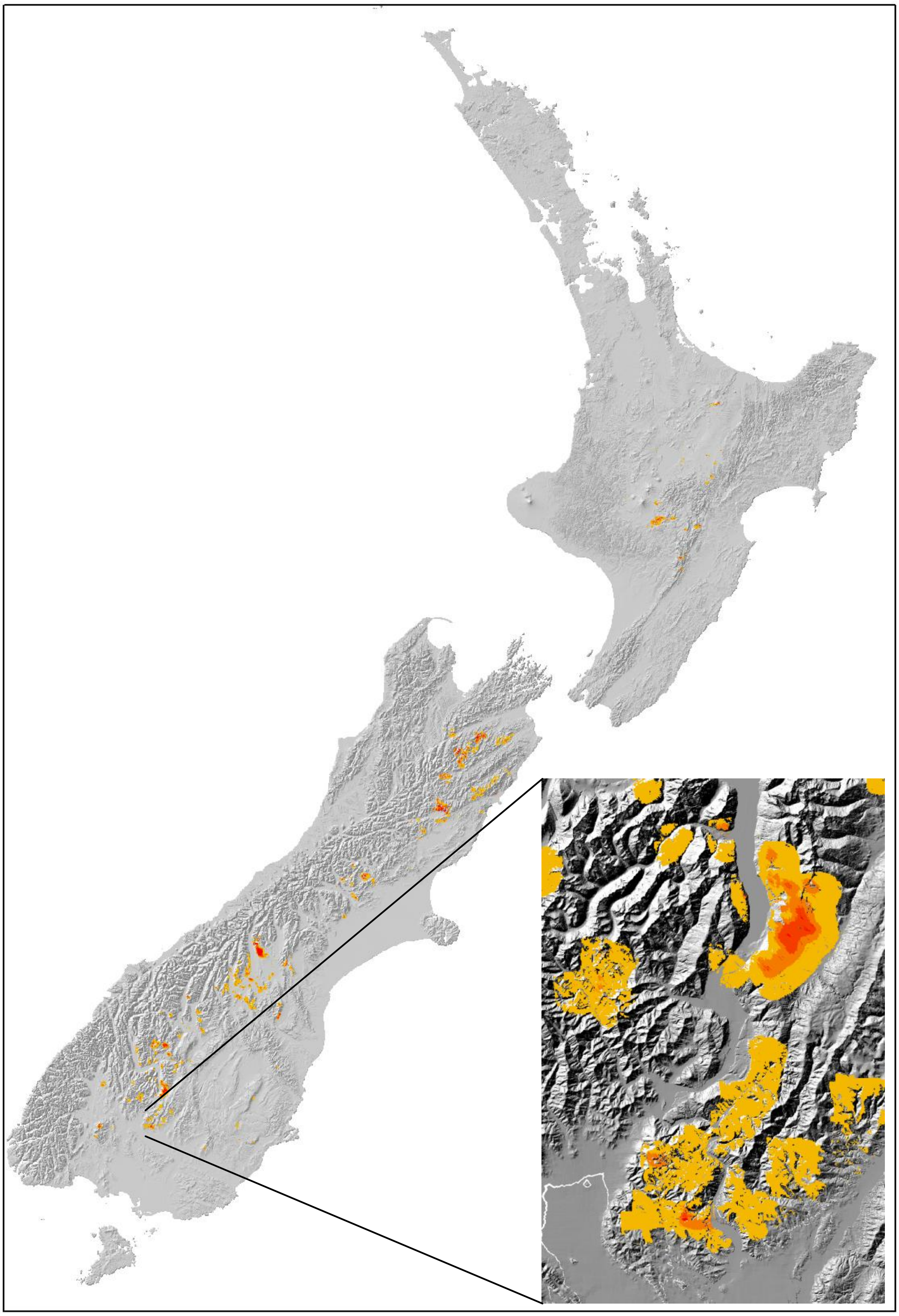
Maps 3 and 4 show the results of the modelling exercise spatially, using scenario 1 with currently seeding kernels (Map 3) and scenario 2 with all known wilding kernels (Map 4) under the assumption of long distance spread. A direct comparison between the maps and their colour intensities is not possible as values are standardised in both cases with different maxima of probability density. However the maps visualise the possible worst case difference in the area that could potentially be affected by short and long distance spread in the future.

Hotspots of spread that can be identified are: The McKenzie Basin west of Tekapo; The Remarkables and their surrounding areas near Queenstown; areas west of Hanmer; the Craigieburn Range and the Kaikoura Ranges in the South Island; and in the North Island; The Kaimanawas and Ruahine Ranges; and areas along the Napier-Taupo Highway; as well as areas surrounding Mount Tarawera in the Bay of Plenty. Most of these areas have been identified by local authorities as areas under wilding risk, and the model runs highlight that if no management is undertaken the risk of infestation and increase in wilding numbers in these areas will be serious and hard to manage once wildings are established and start seeding.

Map 3: Spatial representation of potential future wilding affected areas, due to short and long distance spread from areas where wildings of seeding age are currently present (red very high probability of infestation; orange medium to low infestation risk).



Map 4: Spatial representation of potentially future wilding affected areas, due to short and long distance spread from current wilding areas of any age (red very high probability of infestation; orange medium to low infestation risk).



3. Wilding Fire Hazard

3.1 Identifying fire hazard stages

We hypothesized that the impact of wilding encroachment on fire risk and hazard is likely to change over time along with vegetation succession, wilding treatment and the surrounding weather and topography.

A review of international literature has identified nine likely fire hazard stages and reveals that over time, fuel characteristics change, and depending on the fire weather conditions, so too will fire behaviour. The fire hazard stages have been listed below in table 5.

Table 4: Suggested fire hazard for the succession of wilding trees on the landscape.

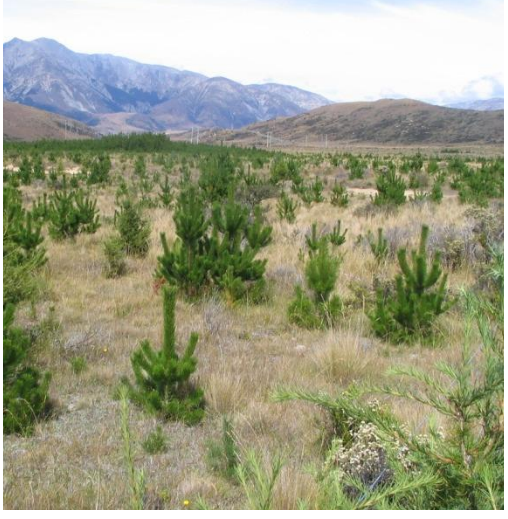
Photo ID	Fire behaviour potential
Open grassland with short scattered seedlings 	The surface grass fuel is the driving factor of fire behaviour. As a result, these areas are more likely to have a high ignition potential and experience high rates of spread and fire intensities compared to closed forests. A wildfire burning in grass fuels typically has a higher intensity than a surface fire in a closed forest, due to faster spread rates but lower fuel loads. Lower fuel moisture contents are experience in closed forests due to sheltering from solar radiation and wind.
Short dense stands 	Fire risk and hazard is likely to be reduced during this stage due to a damper microclimate. Replacement of grasslands into dense wilding conifer stands is likely to correspond to a shift from fast moving to slow moving surface fires (as wind is reduced in a forest environment and forest floors are generally moist). As fuel heights increase with taller woody vegetation, flame heights and fire intensities are also expected to increase.

Photo ID	Fire behaviour potential
Medium height scattered stands 	These areas are more likely to have a high ignition potential and experience high rates of spread and fire intensities compared to closed forests. Where there is space between tree crowns, the opportunity for a moving crown fire is low. Intermittent crowning (or torching) is very likely of individual trees or small groups of trees.
Medium height, dense stands 	For this fuel type, the tree crowns likely touching and height of trees are greater than 1m tall. There is also presence of understory grass and scrub fuels. A wildfire would move through a closed forest with varying speed and intensity with depending on fuel and weather conditions. In times of drought and extreme fire weather, fuels become drier, resulting in easier ignition and more available forest fuels to burn.
Tall dense stands 	For this fuel type, crown fire transition fuels are abundant. Stand age will affect predicted fire behaviour through the amount of fine fuel build up. When extreme fire weather conditions occur, a surface fire could spread faster and can transition into a crown fire. In windy conditions, the potential for spot fires would increase. The concentration of woody fuels would provide a tremendous heat source together with interconnecting crowns creating a high potential for crown fire.

Photo ID	Fire behaviour potential
Chemically treated, Red Stage (1-3 years after treatment) 	The international literature suggests that changes in stand structure and fuel characteristics occur over the course of time. These forests are usually more flammable than live forests. A crown fire could ignite and spread more easily, and have sustained fire propagation under less extreme fire weather compared to live forests. The total amount of fuel is relatively unchanged compared with the green forest; however the amount of available fuel is considerably higher. Foliar moisture is also now considerably lower and responds to changes in weather more easily.
Chemically treated, Grey Stage (4 -10 years after treatment) 	By this stage, there is little fine fuel remaining in the canopy to support a crown fire. The needles have all fallen to the floor and the tree now appears "grey". The fallen needles now provide fuel for a ground or surface fire, although this will have lower intensity. Falling snags (tree branches or stems) can pose serious risks to fire fighters mopping up on the fire line especially during strong winds and after the passage of the fire front.
Chemically treated, Old Stage (10 + years after treatment) 	Large concentrations of downed woody fuels now increase surface fire intensities and make for difficult fire suppression. Under dry conditions, less shade and an increase in wind speeds promotes drier surface fuels and increases the amount of fuel available to burn. Under normal conditions, increased exposure to rainfall would result in higher moisture contents in surface fuels, so that fire intensities and flame lengths are less than they could be at the end of the red stage.

Photo ID	Fire behaviour potential
Felled wildings 	High fuel loadings from felled trees contribute to high intensities, especially when combined with other lighter vegetation present. High loadings typically exist for 1-3 years after felling, but decrease over time as elevated dead needles fall off and decompose. Spread rates are likely to change from slow moving fires in standing green forests, to fast moving fires in wilding slash.

3.2 Identifying suitable models

A literature review was undertaken to identify suitable fire behaviour models for use in New Zealand wilding conifer fuels. The current New Zealand fire behaviour models (from Pearce et al., 2012) for exotic plantation forests are considered to poorly represent wilding fuels due to the differences in fuel characteristics. This presents problems to fire managers responsible for developing suppression strategies during fires in these wilding fuel types.

A final list of models that could be suitable or calibrated to predict fire behaviour in wildings is included below. The models were selected based on the stand structure and fuel conditions, particularly for the fuel layer carrying the fire, instead of just representing a particular species.

Comparisons of suitable international models for use in New Zealand are difficult due to the very different inputs required in the equations. This is particularly the case, where different fire danger rating systems are used, which utilise different weather and fuel measurements, fuel moisture components and fire behaviour relationships to produce quite different fire spread rate and intensity estimates.

We classed available fuel load, rates of spread and head fire intensity into various categories to describe the likely fire hazard (see tables overleaf). To undertake comparisons with each fire behaviour model, a worst case scenario for fire weather (high winds & dry fuels) was assumed.

A final list of 44 models that could be suitable or calibrated to predict fire behaviour in wildings is included in Table 6. This list is a summary table that describes fire hazard qualitatively. In summary, the grass models tend to have faster rates of spread than the less dense and dense forest models.

Assumptions:

- **Maximum Wind speed**: 32 km/h (20 mi/h)
- **Fine Fuel Moisture Content (FFMC)**: 97 - which equates to a 10 hr dead fuel moisture content of 4%
- **Degree of curing (DoC):** 90%
- **Initial Spread Index (ISI):** 50
- **Buildup Index (BUI):** 80

Available fuel load (AFL):

- Light (0 – 5 t/ha)
- Moderate (5 – 10 t/ha)
- Heavy (10+ t/ha)

Rate of spread (ROS):

- Slow (0 – 100 m/h)
- Moderate (100 – 400 m/h)
- Fast (400 – 1,000 m/h)
- Very fast (1,000 – 3,000 m/h)
- Extremely fast (> 3,000 m/h)

Fire intensity:

- Low (0 – 1.2 m),
- Moderate (1.2 – 2.4 m),
- High (2.4 – 3.7 m),
- Very high (3.7 – 7.6 m),
- Extreme (> 7.6 m)

Table 5: summary of suitable international models for fire behavior in wildings.

Fuel model	AFL	ROS	Intensity
Open grassland with short scattered seedlings:			
Ungrazed pasture NZ – Pearce et al. (2012)	light	extremely fast	very high
O-1b: Natural standing grass Canada - FCFDG (1992)	light	extremely fast	very high
PRAD 01: First Rotation (0-3 yrs) Australia - Cruz, de Mar et al. (2011)	moderate	extremely fast	extreme
Fire behaviour fuel model 2 US - Anderson (1982)	moderate	extremely fast	extreme
Short dense stands seedlings:			
Immature pine, age 1-4 (1st rot.) NZ – Pearce et al. (2012)	light	extremely fast	very high
Fire behaviour fuel model 5 US - Anderson (1982)	moderate	moderate	moderate
Medium height, scattered stands:			
Immature pine, age 1-4 (1st rot.) NZ – Pearce et al. (2012)	light	extremely fast	very high
Immature pine, age 5-10 NZ – Pearce et al. (2012)	heavy	extremely fast	extreme
Fire behaviour fuel model 2 US -Anderson (1982)	moderate	extremely fast	extreme
GR6 (106): Grass US -Scott & Burgan (2005)	moderate	extremely fast	extreme

TU3 (163): Timber-Grass-Shrub US -Scott & Burgan (2005)	moderate	extremely fast	very high
TU4 (164): Dwarf Conifer + Understory US -Scott & Burgan (2005)	heavy	very fast	very high
Medium height, dense stands:			
Immature pine, age 11-20 NZ – Pearce et al. (2012)	heavy	very fast	very high
Immature pine, age 5-10 NZ – Pearce et al. (2012)	heavy	extremely fast	extreme
C-4: Immature jack or lodgepole pine. Canada - FCFDG (1992)	heavy	extremely fast	extreme
PRAD 02, 1st rotation – unpruned (4-8 yrs) Australia - Cruz, de Mar et al. (2011)	light	extremely fast	extreme
PRAD 03, Unpruned (8-12 yrs) Australia - Cruz, de Mar et al. (2011)	moderate	extremely fast	extreme
Tall dense stands:			
Mature Pine, age 20+ NZ – Pearce et al. (2012)	heavy	very fast	very high
C-3: Mature jack or lodgepole pine Canada - FCFDG (1992)	heavy	extremely fast	extreme
C-6: Conifer plantation. Canada - FCFDG (1992)	heavy	very fast	extreme
PRAD 04, Unthinned (14-20 yrs) Australia - Cruz, de Mar et al. (2011)	moderate	extremely fast	extreme
TL3 (183): Moderate Load Conifer Litter US - Scott & Burgan (2005)	light	slow	low
TL8 (188): Long-Needle Litter US - Scott & Burgan (2005)	heavy	fast	high
Chemically treated stands, (red stage):			
M-4: Dead Mixedwood green Canada - FCFDG (1992)	heavy	extremely fast	extreme
TU4 (164): Dwarf Conifer +understory US - Scott & Burgan (2005)	heavy	very fast	very high
TL5 (185): High Load Conifer Litter US - Scott & Burgan (2005)	light	fast	moderate
Chemically treated stands (grey stage):			
M-4: Dead Mixedwood green Canada - FCFDG (1992)	heavy	extremely fast	extreme

Fire behaviour fuel model 9 US - Anderson (1982)	moderate	slow	moderate
TL4 (184): Small Downed Logs US - Scott & Burgan (2005)	light	slow	low
TL5 (185): High Load Conifer Litter US - Scott & Burgan (2005)	light	fast	moderate
Chemically treated stands (old stage):			
M-3: Dead Mixedwood leafless Canada - FCFDG (1992)	heavy	extremely fast	extreme
Fire behaviour fuel model 11 US - Anderson (1982)	heavy	fast	moderate
Fire behaviour fuel model 12 US - Anderson (1982)	heavy	very fast	very high
TL7 (187): Large Downed Logs US - Scott & Burgan (2005)	light	slow	moderate
Felled wildings:			
Logging Slash NZ – Pearce et al. (2012)	heavy	extremely fast	extreme
S-1: Jack or lodgepole pine slash Canada - FCFDG (1992)	heavy	extremely fast	extreme
S-2: White spruce - balsam slash Canada - FCFDG (1992)	heavy	very fast	extreme
PRAD 01: Second rotation (0-3yrs) Australia - Cruz, de Mar et al. (2011)	light	fast	very high
PRAD 06: Post clear fall – harvested site Australia - Cruz, de Mar et al. (2011)	heavy	very fast	extreme
Fire behaviour fuel model 13 US -Anderson (1982)	heavy	extremely fast	extreme
SB1 (201): Low Load Activity Fuel US - Scott & Burgan (2005)	light	fast	moderate
SB2 (202): Low Load Blowdown US - Scott & Burgan (2005)	heavy	very fast	very high
SB3 (203): Blowdown US - Scott & Burgan (2005)	heavy	extremely fast	extreme
SB4 (204): Blowdown US - Scott & Burgan (2005)	heavy	extremely fast	extreme

3.3 Wilding Fire Behaviour

A hypothetical scenario was used to compare the fire behaviour predictions using identified models. This hypothetical scenario is based in Tekapo, located in the Mackenzie basin of the South Island, where an area of grassland (ungrazed terrain) is being invaded by wilding conifers. The aim is to display hypothesized trends in fire hazard over time with the invasion of wilding seedlings through to dense unmanaged wilding forest cover.

This scenario is based on:

- FWI indices for each level of fire danger rating (Table 6)
- Comparison of fire behaviour predictions from models (Table 5)

We used New Zealand fuel models to represent the changes of fuel structure over time. Four "fuel stages" were hypothesized for this scenario, where over time:

1. An open grassland was invaded by young short scattered seedlings – modelled using NZ ungrazed pasture;
2. The area filled in with immature medium height scattered stands (crowns not touching) – modelled using NZ Immature Pine 5-10 years;
3. The medium stands grew taller and denser, with the crowns now touching – modelled using NZ immature pine 11-20 years; and
4. The medium height stand grew even taller to become a mature dense wilding forest – modelled using NZ mature pine 20+ years.

Table 6: Summary table where values are derived from Appendix 2 using the approach by Alexander (2008) in Annex 3; except Mt Cook 2008 which is actual fire weather data obtained from the NRFA fire weather system.

Fire Danger level	ISI	BUI	DoC %
Low	2	10	52
Moderate	5	30	65
High	9	50	70
Very high	12	65	80
Extreme	20	100	90
Extreme 2	25	120	95
Mt Cook 2008	56	129	90

Fire Hazard scenario #1

Figure 7 illustrates hypothesized trends in fire hazard across a range of fire danger ratings (levels) for the scenario described above. In summary, across all the fire danger levels, medium height scattered wildings would pose the most serious fire hazard (highest spread rates and intensities).

Wilding control treatment stages were not included as none of the current NZ fuel models are deemed to be representative of chemically treated wilding stands. It is also not currently possible to utilise the suggested US models due to these requiring very different fire danger ratings and fuel moisture inputs.

Available Fuel Load

- The fuel load for open grassland with short scattered wildings is assumed to stay constant (at 3.5 t/ha) no matter what the fire danger level, or at least very comparatively little.
- In contrast, fuel loads for the forested fuel types increase as the fire danger level increases, and fuels dry out.
- A medium height scattered wilding forest was found to have the highest available fuel loads across each of the fire danger levels.
- A dense mature forest has the lowest fuel loads at lower fire danger levels, but increased to the second highest as the fire danger reached extreme levels.

Rate of Spread

- As fire danger levels increase (from Low to Extreme) so too does the Rate of Spread (ROS) in all the four fuel stages.
- Under extreme fire weather conditions, the open grassland and medium scattered fuel stages had identical head fire ROS and were the fastest at each fire danger level. This is because both used the same underlying grassland model.
- Both medium and tall dense forests had the same and the lower ROS. This is because both were based on the same mature pine ROS model.

Head Fire Intensity

- As the fire danger level increases, so too does the predicted head fire intensity for each of the fuel stages.
- Interestingly, the medium scattered wilding forest was predicted to have the highest head fire intensity out of the four stages across all fire danger levels, but especially under extreme fire weather conditions.
- The intensity for this fuel stage during the Mt Cook station fire weather was off the chart, and predicted to reach a maximum value of 250,000 kW/m.
- The open grassland was predicted to have the lowest intensity, reaching a maximum of 17,000 kW/m.

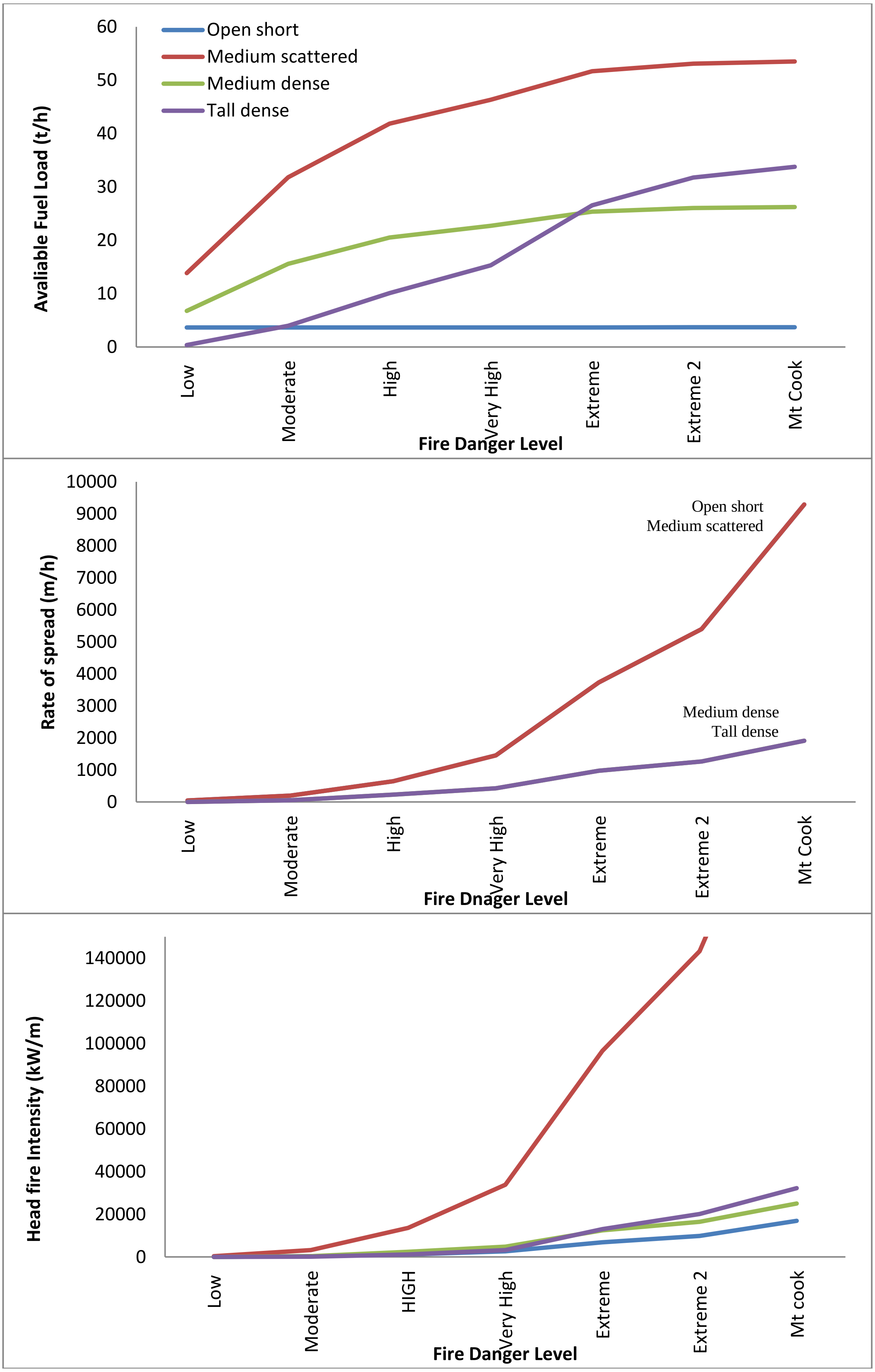


Figure 7: Hypothesized trends in fire hazard with changes in fire danger levels.

Fire Hazard scenario #2

Figure 8 illustrates the potential changes of fire hazard under extreme conditions (from Table 3) for each fuel stage. This figure attempts to show the transition from one fuel stage to another. The relative changes are derived from the qualitative comparisons in Table 6 supported by the quantitative comparisons predicted for the Tekapo fire climate scenario in Figure 7.

Here, fire behaviour in treated stands (chemicals or felling) has been included for comparison purposes, with estimates of fire behaviour potential based on the qualitative information provided from the review of the available literature.

In summary, the results showed a fair amount of variability for each of the wilding fuel type stage based on both local and international models with respect to available fuel load, rate of spread and intensity. This shows that fire hazard in wilding stands is still poorly understood and further work is needed.

Available Fuel Load

- The top graph shows that available fuel load is at its highest for the Felled stage and lowest for the early invasion (Open short and Short dense stages).
- The Red stage was expected to have considerably higher available fuel load than what is predicted, suggesting the models used for this fuel stage may not be entirely appropriate.

Rates of spread

- The middle graph shows that the fastest spread rate occurs in the early invasion stage (Open short) and the slowest is in the grey stage.
- The red, grey and old stages were expected to have slightly higher spread rates than predicted, again suggesting possible issues with the models used.

Intensity

- The bottom graph shows that the highest intensities are predicted for the Medium height dense stands and lowest for the Short dense stands.
- Again, the Red stage was expected to have higher intensities than the Tall dense forest since the amount of available fuel is thought to be considerably higher.

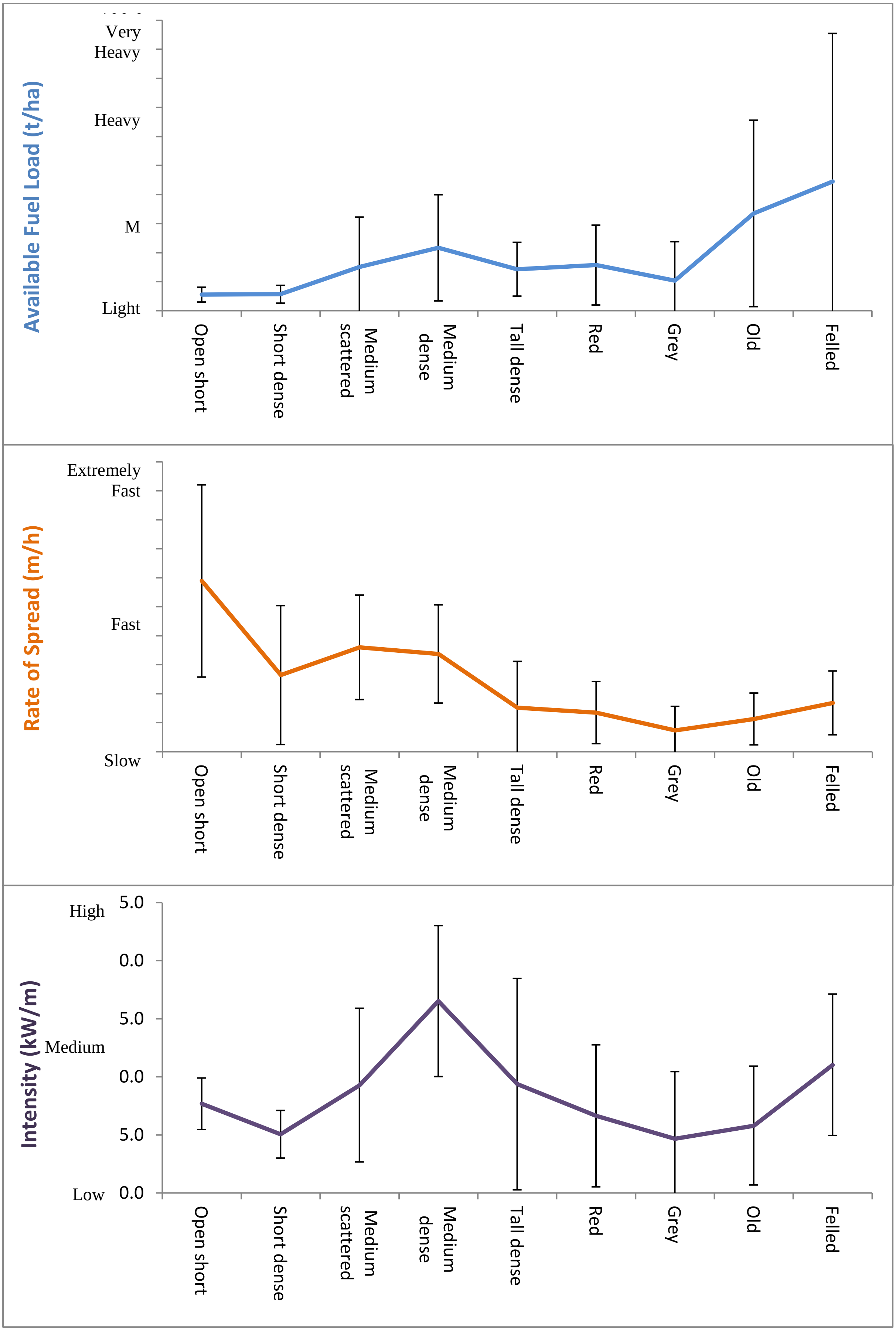


Figure 8: hypothesized trends of fire hazard for various fuel stages during Extreme weather.

Conclusions and Recommendations

The objectives of this research were to:

- Define the geographical distribution of wildings in NZ high country
- Describe the fire hazards associated with wildings and their control
- Address the perception that wilding conifer spread increases the fire hazard over the vegetation types that they are replacing
- Provide information for land and rural fire managers on the likely issues, effects and impacts of wilding conifers, based on their current geographical distribution and potential future spread
- Transfer knowledge to practitioners to enable effective hazard management.

In summary, we now have an improved knowledge on the geographical patterns of wilding conifer spread and its potential impacts on current and future spread. We also have a way forward in predicting fire hazard and potential fire behaviour for wilding conifers in New Zealand landscapes. A description of fuel loads and fire behaviour were collated that could be used in conjunction with fire weather to model fire behaviour in wilding conifer stands. We have made a number of recommendations to further our knowledge on fire hazard in wildings. Future research will provide, with greater certainty, information for fire managers and property developers on the potential impacts wilding spread and growth have on fire hazard and risk.

Literature review

The literature review aimed to summarise the current state of knowledge on the fire hazard associated with wilding conifers and conifer spread in New Zealand. Until now, the effects of wilding spread and their control on fire behaviour have not been studied in New Zealand. There is a noticeable lack of research on how fire hazard changes over time with wilding invasion, or comparing fire behaviour pre and post wilding control.

The widely held view is that wilding trees increase the fire hazard. The impact of wilding encroachment on fire risk and hazard is likely to change over time along with vegetation succession, wilding treatment and the surrounding weather and topography. Control measures are likely to increase the amount of dead fuel present, therefore creating an even greater fire hazard compared to live wilding trees.

The international literature investigating the effects of insect attack, tree mortality and fire behaviour in conifers is building in size and may give us an idea on the potential risk and hazards for treated wilding conifers. However, researchers and fire managers must apply these theories with caution to wildings and their control, due to the differences in stand structures and effects.

A wilding invasion presents problems not only for land managers in controlling the spread of these wildings, but also has implications for fire fighters and fire managers. It was hypothesized that wildfires in these areas could exhibit more extreme fire behaviour, will be more difficult to suppress, and present greater threats to lives and property.

It was also hypothesized that wilding control methods could increase the fire risk and fire hazard and threaten life and property in rural-urban communities, key recreational areas for tourism, conservation land, plantations and farmland.

Distribution of wildings

This study described the current critical area and potential future extent for wilding affected land. The results provide a good baseline to describe the current extent of wilding conifers. The current spatial database created identified 321,756 ha of wilding infestation. Over the last 10 years, there has been a marked increase in area affected by wilding conifers, in the South Island especially.

Assuming that no control is undertaken, by 2020 the potential future wilding infested area could increase by an additional 150-160,000 ha. Generally the highest increase would occur in the South Island as there are less intense grazing regimes and more susceptible vegetation types available.

Hotspot areas note worthy for fire managers and property developers identified were the McKenzie Basin west of Tekapo, the Remarkables and their surrounding areas near Queenstown, areas west of Hanmer, the Craigieburn Range and the Kaikoura Ranges of the South Island. North Island hotspots were the Kaimanawas and Ruahine Ranges, areas along the Napier-Taupo Highway, as well as areas surrounding Mount Tarawera in the Bay of Plenty.

We noted that our results varied from estimates made by previous mapping exercises and expert knowledge. Therefore, further improvements could be made. In particular, a validation of current wilding occurrences based on ground truthing could improve the confidence in our results. Further research could include:

- Use of new remote sensing techniques (i.e. LiDAR) for indentifying wilding affected areas, tree density and assisting with quantifying fuel loads and structure.
- Surveying areas not included in this study (due to being highly fragmented or small in size) using randomly placed survey plots, as well as other areas that are coming to attention as potentially containing wildings.
- Including data for spread prone species that are present in shelterbelts, plantations and woodlots.
- Inclusion of critical variables like terminal velocity and fecundity for different species in the analysis. This would require the extensive collection of field data for certain species (e.g. Douglas-fir) and understanding of the underlying causes of coning intensity.

Wilding Fire behaviour

Fire hazards predicted by the New Zealand pine plantation models from Pearce et al. (2012) are currently the best available for wildings in New Zealand. However, a key finding from the Mt Cook wildfire case study (Clifford and Pearce, 2009) was that the current New Zealand fire behaviour models for plantation forests are not applicable to wilding fuels, and that further work is required to identify or develop more accurate models. The review of international literature identified a number of potential fuel models for predicting fire behaviour in wildings.

The perception that wilding spread increases the fire hazard as they replace other vegetation types is true in the early stages where young scattered stands become more dense and taller. But over time, as a wilding forest forms we see a shift from high to lower rates of spread and fuel loads. This results in medium density wilding stands having the highest overall fire intensities.

The results also show that fire hazard in wilding conifers are dynamic, meaning that the fire weather conditions (Low to Extreme) as well as the stage of invasion or treatment has a strong effect on available fuel load, rate of spread, and intensity. It is expected that fire hazard will be affected by seasonal conditions, with differences between wet and dry seasons. With the impacts of climate change, more days of Very high and Extreme danger are to be expected (Pearce, Kerr et al., 2011). This means that we are to expect a greater chance of extreme fire behaviour in wilding affected areas, especially in taller (medium height) open wilding stands.

We recommend one of two options to move forward:

The first option is to develop new accurate models to assess how fire behaviour changes with wilding invasions and their control. This would be done by collecting fuel data (moisture and loading) along with fire behaviour observations in wildings of different species, ages and densities. The observed data could be collected from experimental burns, prescribed burns and wildfires.

The second option is to utilise existing models from New Zealand or overseas and reverse engineer the equations by modifying the models to fit observations. This option will minimise development time and provide an interim solution in the short term. Researchers must apply this approach with caution to treated and untreated wildings, due to the differences in stand structures. These models should then be tested with actual fire behaviour observations in the field to accurately assess the suitability for predicting fire behaviour in wilding affected areas.

Which approach is most appropriate will depend on availability of data, including wildfires and experimental burn opportunities in both treated and untreated wilding stands. However, in the short-term the reverse engineering of local or international models may offer the best solution until more comprehensive data sets are available.

In conclusion, we recommend that it is important to undertake future research into the distribution and fire behaviour in wildings. This is to provide accurate information for property protection and land management measures to reduce the risk of fire. This information could be vital for planning guidelines (e.g., for subdivision design, town planning) and educational information (e.g., brochures on fuel management, defensible space).

Additional fire research studies on wildings could also include:

- ecological investigations into impacts of wilding control (how it affects succession of vegetation types),
- determining fire behaviour for forests affected by diseases or pests (i.e. red needle cast, or insect damage),
- how to conduct safe and effective controlled/prescribed burns.

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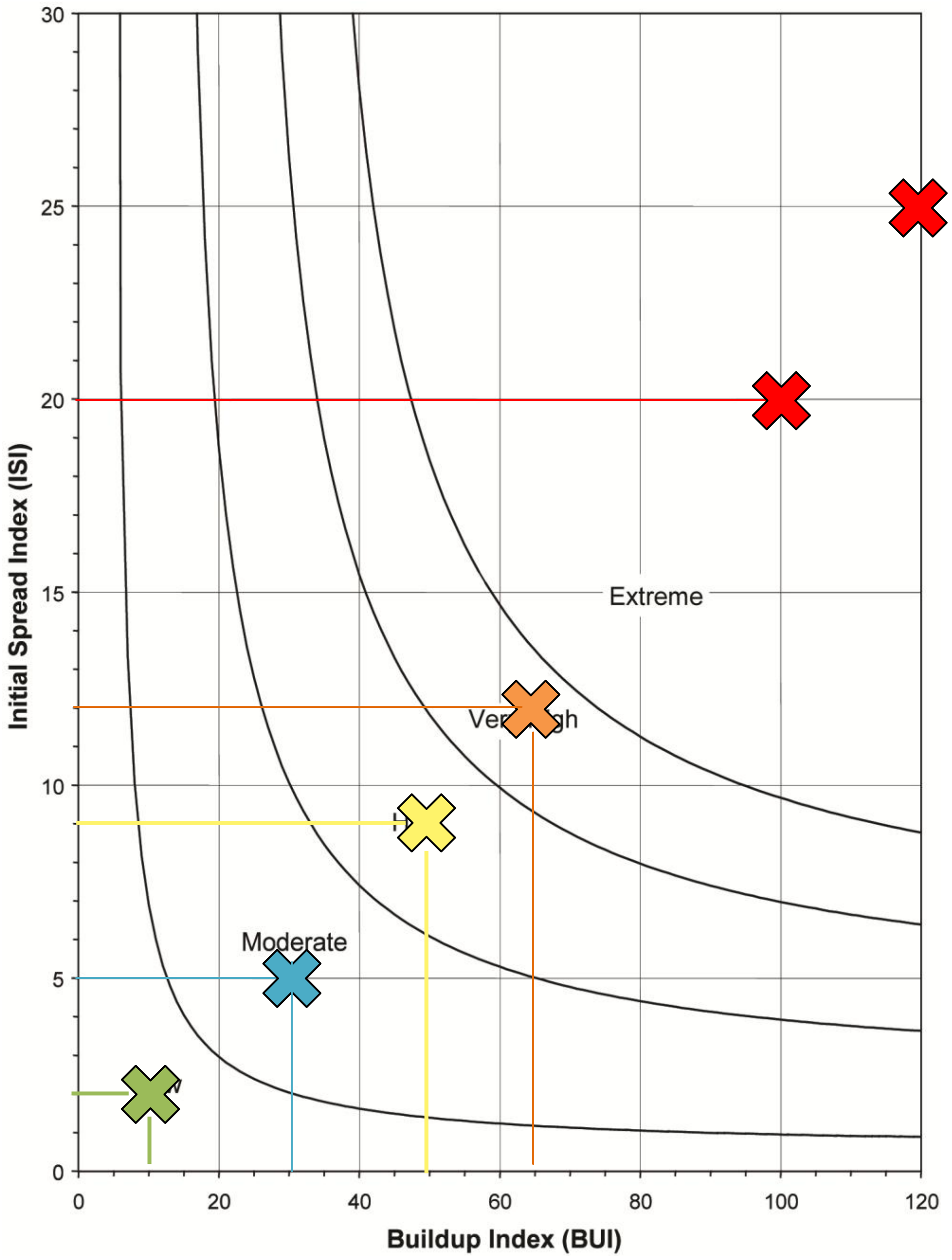
Appendix

Appendix 1. Adapted from Alexander (2008) & Wildland Fire Assessment System http://www.wfas.net/

Fire Danger Rating	Fire danger class descriptions
Low (L)	A fire is unlikely to sustain itself due to moist fuel conditions. Fuels do not ignite readily from small firebrands. However, ignitions can occur near prolonged or intense heat sources (camp fires, slash piles, lightening). Fire's spread slowly by creeping or smouldering, and burn in irregular fingers. A fire generally does not spread much beyond its point of origin, and if they do, control is easily achieved. There is little danger of spotting. Minimal involvement of deeper fuel layers or larger fuels. Controlled burns can usually be executed with reasonable safety.
Moderate (M)	Fuels can sustain ignition and combustion from flaming and glowing firebrands. Creeping or gentle surface fire activity is common. Fires in open cured grasslands will burn briskly and spread rapidly on windy days. Forest fuels are drying and there is an increased risk of surface fires starting. Timber fires spread slowly to moderately fast. The average fire is of moderate intensity, although heavy concentrations of fuel, especially draped fuel, may burn hot. Short-distance spotting may occur, but is not persistent. Fires are not likely to become serious and control is relatively easy. Control of such fires can become troublesome and costly if not attended to immediately. Direct manual attack around the entire fire perimeter with hand tools and pumps is possible.
High (H)	Running or vigorous surface fires are most likely to occur. Any fire outbreak is a serious problem. Unattended brush and campfires are likely to escape. New fires may start easily, burn vigorously, and challenge fire suppression efforts. Open burning and industrial activities may be restricted. All fine dead fuels ignite readily and fires start easily from most causes. Forest fuels are very dry and the fire risk is serious. Fires spread rapidly and short-distance spotting is common. High-intensity burning may develop on slopes or in concentrations of fine fuels. Control becomes more difficult if it's not completed during the early stages of fire growth. Water under pressure (from tankers or pumps with hose lays) and bulldozers are required for effective action.
Very High (VH)	Fires start easily from all causes and, immediately after ignition, spread rapidly and increase quickly in intensity. Spot fires are a constant danger. Likelihood of intense surface fires is a distinct possibility; torching and intermittent crowning in forests can take place. Fires burning in light fuels may quickly develop high intensity characteristics such as long-distance spotting and fire whirlwinds when they burn into heavier fuels. Direct attack is feasible for only first few minutes after ignition. Otherwise limit to helicopters or fixed wing aircraft and fire retardants.
Extreme (E)	Fires start quickly, spread furiously, and burn intensely. All fires are potentially serious. Expect explosive fire behaviour – rapid spread rates, crowning in forests, long-range spotting, fire whirls. Development into high intensity burning will usually be faster and occur from smaller fires than in the very high fire danger class. Fires that develop headway in heavy slash or in conifer stands may be unmanageable while the extreme burning condition lasts. Direct attack is rarely possible and may be dangerous except immediately after ignition. Effective and safe control action is on the flanks until the weather changes or the fuel supply lessens.

Appendix 2a - ISI and BUI determine each fire danger category for Forest fire danger



Appendix 2b- ISI and Curing determine each fire danger category for Grassland fire danger