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Understanding the effect of afforestation on wildfire risk and hazard within New Zealand landscapes

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Native forest condition following the 2019 Pigeon Valley Fire.

Report information sheet

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Executive Summary

This report was commissioned by the Parliamentary Commissioner for the Environment to review how afforestation influences wildfire risk and hazard within New Zealand landscapes. This report summarizes the current state of knowledge around wildfire risk and hazard from afforestation at both the stand and landscape scale. In this synthesis the term ‘afforestation’ is used broadly and includes both re-forestation and natural regeneration.

New Zealand is on a similar wildfire trend to the rest of the world, where wildfire intensity, severity, and frequency have all been increasing and are predicted to continue to do so. In New Zealand, approximately 40,600 ha have burned in 118,700 wildfires between 1998 to 2023. There were more wildfires started on the North Island, but more area burned on the South Island. Ninety-eight percent of these wildfires were ignited by humans where the greatest ignition risk has been due to prescribed fire. Landscape context is critical as ignitions can occur in both the forest itself and on adjacent land, particularly where the forest is surrounded by grasslands. Most wildfires in plantation forests do not originate from forestry activities, but rather come from external sources.

Wildfire is a complex landscape disturbance that is influenced by the fire environment (topography, fuels, and weather), with weather considered the most changeable and influential of rapid changes in fire behaviour. The fire environment is important for afforestation because it influences fuel availability, ignition susceptibility, and fire behaviour at the landscape scale. The likelihood of wildfire ignition and subsequent spread is influenced by human activities and the vegetation mosaic (e.g. forest patch size, proximity to other vegetation types, age of forest stand). Wildfire hazard and risk changes seasonally, annually, and decadally as the fuels change. The intensity of the fire and rate of spread are influenced by the forest composition, age, and stage. Wildfire risk changes with land use and as the forest ages. In general, early seral forests are easier to ignite and have rapid rates of spread due to the abundance of grass and flammable scrub species intermixed with the seedlings/saplings.

As forests age, the forest canopy closes creating a moist microclimate that makes ignition less likely, however when ignition is successful, older forests will often burn at higher intensities compared with early seral stands due to an increased fuel load and fuel height. These generalizations vary based on species present. In New Zealand larger late seral forest patches with a lower edge to interior ratio may reduce wildfire hazard because the tall canopy of older forests provides a buffering effect on fuel moisture retention which reduces ignition potential and subsequent spread. However, under drought conditions when these forests do ignite there tends to be greater vertical and horizontal fuel continuity for fire to spread, increasing the potential for a higher intensity fire because native forests, especially beech forests, have much greater fuel biomass compared to other forest types. General, qualitative recent observations indicate that continuous canopy burning of native forests is rare, however historical land clearing burns that ‘got away’ describe wildfires that were out of control, particularly during times of drought.

Forests in New Zealand can be impacted by localized/point disturbances (individual tree scale) to landscape wide destructive events (stand level). Large scale events can alter the wildfire hazard and resulting fire behaviour. Multiple abiotic and biotic factors can negatively impact forest health. Forests impacted by stressors or natural disturbances are assumed to be more flammable than a healthy forest, due to a reduction in foliar moisture content, and an increase in the amount of dead material present, therefore posing a greater wildfire hazard compared to healthy forests. The change in hazard and wildfire potential differs based on the amount of disturbance and or stress to the stand. Any one or a combination of these stressors can initiate dieback, and initial mortality from one stressor may lead to further mortality from another. Wildfire as a disturbance can create a feedback cycle, whereby without intervention, future wildfires are likely to ignite and spread with increased ease as grasses, weeds, and scrub move into the landscape. This increased risk will remain until forests mature into late-seral – old growth which can take multiple decades or centuries, depending on the site context, species and scale of the disturbance, although anthropogenic intervention such as reforestation can speed up recovery.

Careful consideration for species type and ‘fuel’ interruption should be considered to assist with reducing wildfire risk. While the right conditions can lead to a wildfire spreading in all forest and non-forest burnable fuels, careful planning at a stand and landscape level can reduce hazard and risk and improve fire suppression activities for when a wildfire does occur. Research has identified that co-developed deliberate fire mitigations improve mitigation success. There are various management strategies and recommendations that have been implemented or recommended by national and local government agencies and bodies, commercial landowners, and private landowners. Planning, fuels management, and education are key reduction and readiness practices to minimize wildfire hazard and risk in New Zealand forests as well as other vegetation types. For example, natural and anthropogenic fuel breaks can break up fuel continuity, adding heterogeneity into the stand or landscape which can to 'interrupt' the spread rate either by slowing the wildfire down or by stopping it entirely.

Understanding the effect of afforestation on wildfire risk and hazard within New Zealand landscapes

Table of contents

Introduction

Scion was commissioned by the Parliamentary Commissioner for the Environment to review how afforestation influences wildfire risk and hazard within New Zealand landscapes. This report summarises the current state of knowledge around wildfire risk and hazard from afforestation at both the stand and landscape scale. In this synthesis the term 'afforestation' is used broadly, and includes both re-forestation and natural regeneration, and these, herein will be referred to as afforestation in general. An increase in forests can increase biodiversity and ecosystem services (e.g. improve soil and water resources) as well as mitigate against climate change and provide an economic value chain.

This synthesis has been developed using a combination of expert knowledge, current data - where available, and national and international literature. At the end of this report there is a glossary specific to key terms within the document. The glossary covers key terms that are important to understand while reading the report. The first time a key term is used in the report there is a direct link to the glossary as noted by hyperlink (blue with an underline).

Contemporary New Zealand Wildfire

New Zealand experienced an increase in the number of wildfires[1] with the area burned being highly variable (Anderson et al., 2008; Gross et al., 2024a). Approximately 40,600 ha were burned in 118,700 wildfires between 1998 to 2023. During (1998-2022) there was an average of 3419 wildfires per year and an average area burnt of 5802 hectares per year (Figure 1). It is important to note that most wildfires are small (<5 ha) with the total area burned often being linked to a couple of large wildfires. For example, the area burned in 2020/2021 was primarily from two wildfires, Ohau and Livingstone. 2019/2020 remains the worst wildfire year[2] on record with 5,994 wildfires, and 1998/1999 remains the worst on record for total area burned (17,694 ha) (Figure 1). Most of the wildfires occur in the North Island, however most of the area burnt occurs in the South Island (Figure 2). This difference is a combination of various factors, including population and fire response, fuels, climate, and weather. While wildfires do burn through forests, most wildfires over the last 34 years have started in grass (Figure 3). In general, over the last 30 years intentionally lit fires for land management (either pile burning for debris removal, or prescribed burning for land clearance) are the primary cause of wildfires. When these intentionally lit fires escape, they are then classified as a wildfire. Between 1991-2022 an average of 31.64% of wildfires in New Zealand are caused from pile burning and an average of 33.38% of the total area burnt are caused from prescribed fire escapes (Figure 4) (Gross et al., 2024a). This is in comparison to only 1.9% of the wildfires and 4% of the burnt area being attributed to natural causes (i.e. lightning or spontaneous combustion[3]). These ignition categories are continually refined as awareness of ignition sources increases. For example, "Powerlines" as a category was not added into the dataset until 2021/2022 but was identified as the leading cause of area burnt in 2020/2021, contributing to a total of 5,666 burned ha (Gross et al., 2024a).

[1] It is important to recognise that some of the increase is due to better reporting of fires.
[2] A fire year runs from 1 July to 30 June of the following year. For example, 1998/1999 is representative of 1 fire year 1 July 1998-30 June 1999
[3] Spontaneous combustion is not always natural as it often happens in woody debris/rubbish piles, however it has been lumped into natural causes for the purpose of the Annual Wildfire Summaries (e.g. Gross et al. 2024 a).

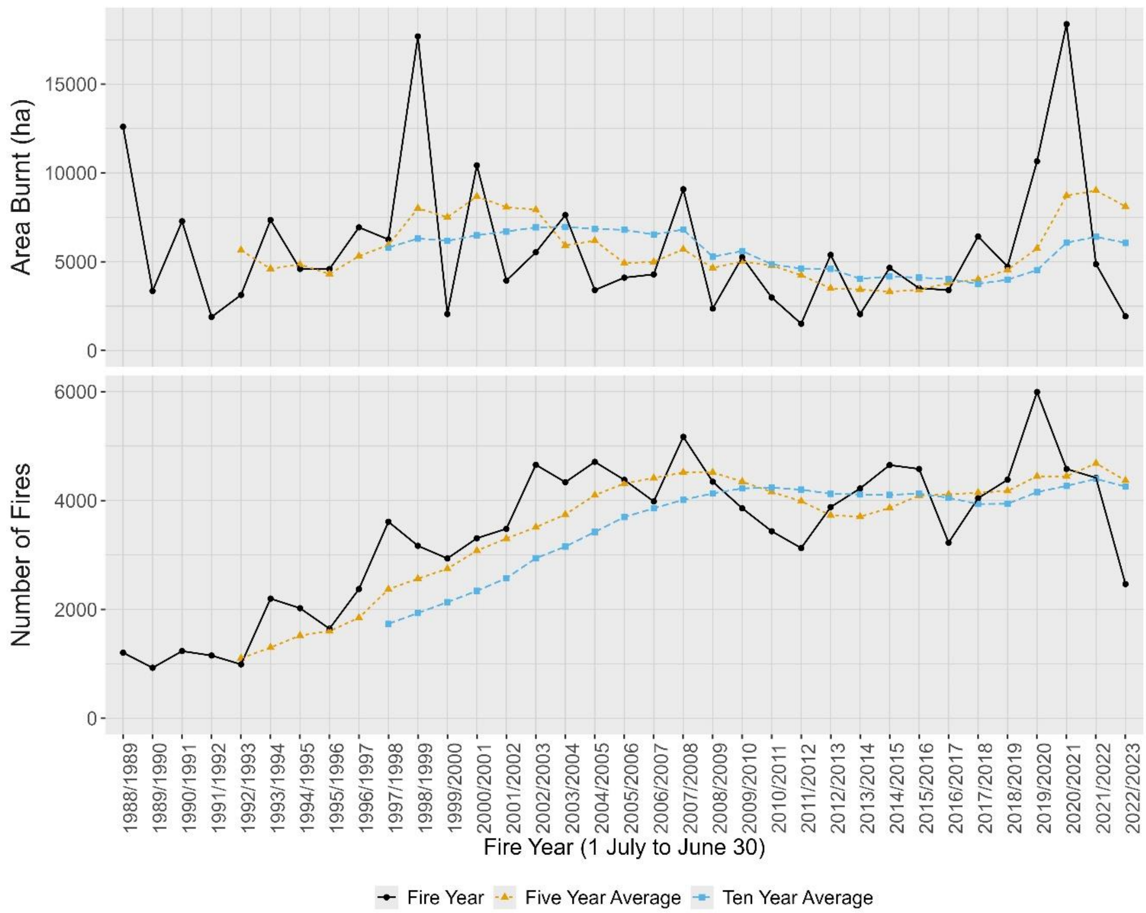

Figure 1. Area burnt (ha) (top) and total number of wildfires (count) (bottom) for the last 34 years (1988/1989 – 2022/2023). Note: this dataset is derived from wildfire emergency responses and does not include vegetation fire non-responses or false alarms that required no action.

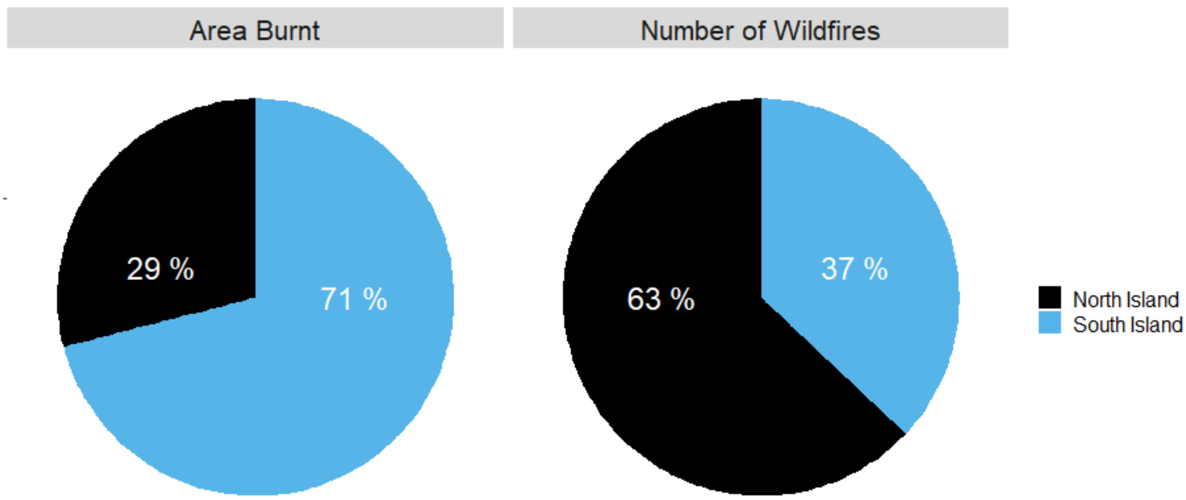

Figure 2. Left: Percentage of average total area burnt attributed to North (black) versus South (blue) Islands and Right: Percentage of average number of wildfires attributed to North (black) versus South (blue) Islands over 29 years (1993/1994 – 2021/2022).

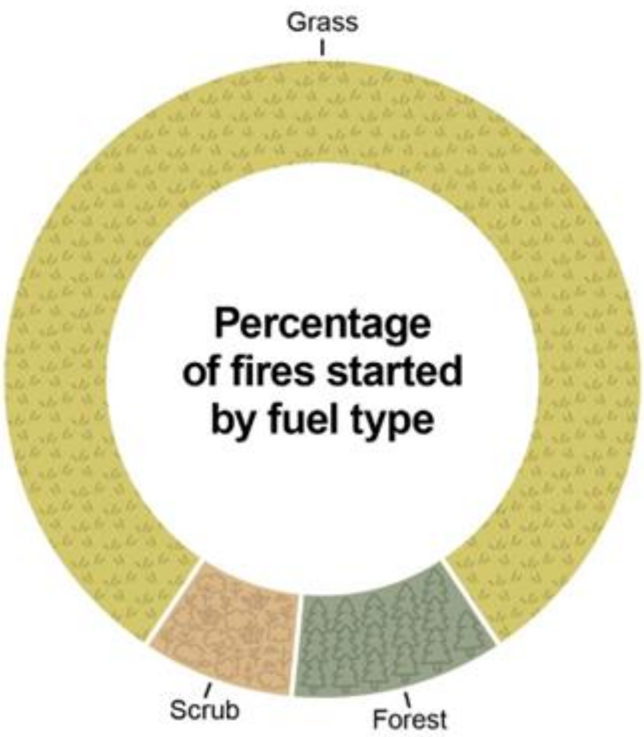

Figure 3. Data sourced from Fire and Emergency NZ based on 34 years of wildfire data (1988/1989 – 2021/2022). and associated Land Cover Database type hosted by Manaaki Whenua Landcare Research. Large spatial datasets inherently have associated inaccuracies, therefore large patterns, rather than absolute values are what is important. For example, there are also well-known issues with locations of wildfire being attributed to the building or property address rather than the actual point of ignition. In addition, land cover changes and changes in vegetation structure and composition are not always reflected in the data. Data challenges and inaccuracies aside, this figure highlights that grass is the dominant fuel (vegetation) where wildfires are first reported.

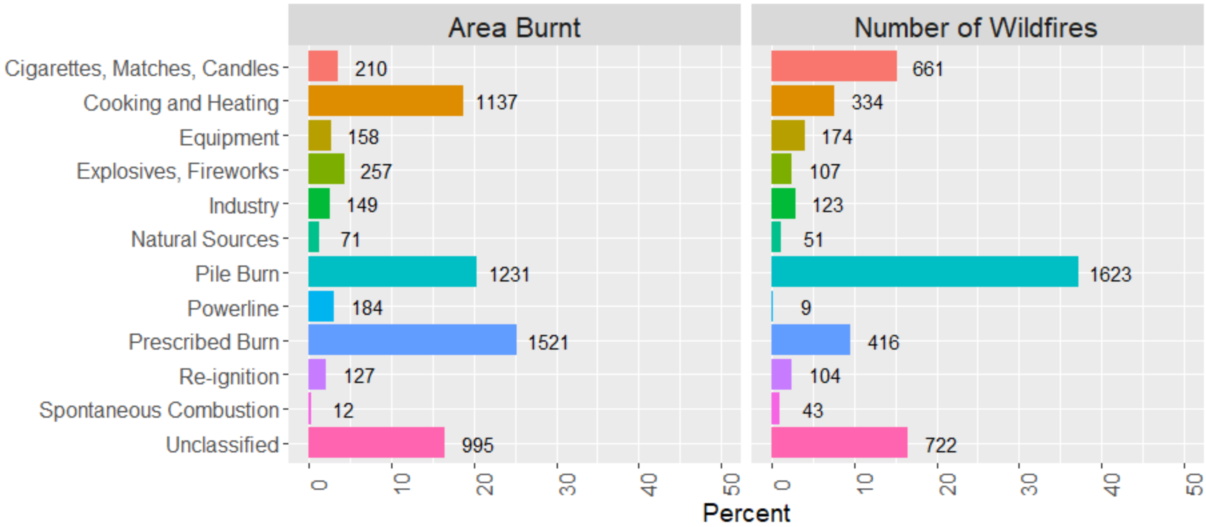

Figure 4. Cause of wildfire ignition and area burnt (1991-2022). Numbers to the right of the bars indicate the annual average while bar length represents the percentage within the category. Powerlines were not separated as their own category until 2020, therefore the average represented does not fully reflect the average across the full record.

Fire

For a fire to ignite you need heat, oxygen, and fuel (Figure 5). All three of these elements are required in sufficient quantities and at the right mixture for a fire to continue to burn and, at their core, all fire suppression strategies seek to disrupt one or more of these components. Once a fire is ignited, how effectively it burns is influenced by the environment in which the fire is burning. Known in combination as the fire environment, weather, topography and fuel interact to encourage or inhibit fire growth, intensity and behaviour (Figure 6) (Countryman, 1972).

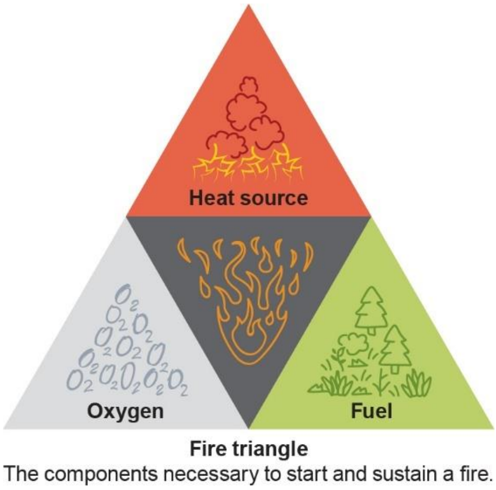

Figure 5. The fire triangle illustrates the three components necessary to start and sustain a fire. Graphic Design Credit: Dale Corbett, Scion.

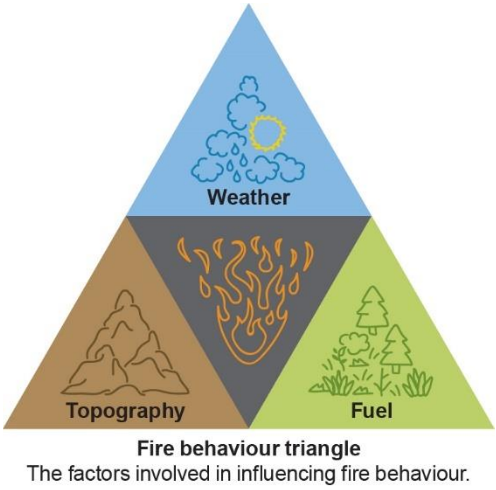

Figure 6. The fire behaviour triangle identifies the key components of the fire environment which influence fire behaviour. Topography, fuel, weather, and the fire itself all determine how the fire will spread and the intensity of the fire. Graphic Design Credit: Dale Corbett, Scion.

There are three main types of fire: structure (e.g. when building is burning), prescribed, and wildfire. In this synthesis we are primarily focused on wildfire – any unwanted or unintentional fire burning in vegetation. However, the broad synthesis of how fire interacts with forests can also include prescribed fire – the controlled application of fire used for specific land management outcomes. Wildfires occur across terrestrial vegetated environments due to both natural and human caused events. Prior to human settlement wildfire occurred infrequently, caused by volcanic activity or lightning, with return intervals in the hundreds or thousands of years depending on the ecosystem (Guild & Dudfield, 2009; Molloy et al., 1963; Ogden et al., 1998; Perry et al., 2014; Sparks et al., 1995). Following the arrival of humans to New Zealand, most wildfire occurrences have been human caused (Anderson et al., 2008), with 40% of the forested area burned in a period of 200 years after human arrival to New Zealand (McWethy et al., 2010; Whitlock et al., 2015).

Once ignited and spreading, wildfires can occur as a ground, surface and/or crown fire based on the fuels present and fire behaviour characteristics. All these fire types occur in New Zealand and a single fire can burn as a single type or can transition between ground to surface or surface to crown fires. Ground fires are often the least known fire but are important fires to be aware of particularly in wetland or peatland soils. Ground fires primarily burning below the surface through smouldering or glowing combustion. These fires are typically slow moving, gradually consuming organic litter and duff soil layers with little to no visible flame. They can be long lasting and difficult to put out if they burn deep into fuels and are sheltered from rain.

Surface fires burn along the ground surface typically spreading with open flames. These fires can spread rapidly and exhibit high intensities when conditions are suitable, consuming surface fuels including litter, coarse woody debris, as well as understory vegetation below the crown canopy such as grass and low scrub. In forests, when a surface fire has sufficient energy to climb from the surface into the raised foliage of the dominant trees, then the fire becomes a crown fire. While crown fires can burn independently of surface fires, it is a rare event with most canopy fires burning with a corresponding surface fire. Crown fires can spread rapidly with high intensity and large flame lengths due to exposure to the full influence of the prevailing winds. Crown fires can burn intermittently "torching" up individual trees, or continuously through the forest canopy. Crown fires can also lead to embers (burning particles of bark, leaves, and branches) being thrown ahead of the fire a short distance or lofted by winds or the fire's convection column hundreds of metres or kilometres ahead of the fire. When the fuel and weather conditions are suitable, these embers will remain lit and land in receptive fuels, creating new spot fires.

Influence of weather on fire and how projected climate change may influence fire behaviour

Of the three elements in the fire environment (Figure 6), weather is considered the most changeable and influential of rapid changes in fire behaviour. Weather influences the availability of fuels through drying and wetting, and the fire behaviour during an ongoing wildfire. The interactions among six standard weather metrics (Air temperature, wind, atmospheric moisture (i.e. relative humidity), precipitation, atmospheric stability, and surface pressure) these factors and the fire environment increase the complexity of how weather influences fire behaviour. Four of these factors (air temperature, winds, atmospheric moisture, and the last 24-hour rain accumulation) are used in the New Zealand Fire Weather Index System (FWIS) to calculate fuel moisture codes and fire behaviour indices that inform on fuel availability and ignition readiness (largely based on fuel moisture) and the potential rate of spread and fire intensity if an ignition occurs (Anderson, 2005). Changes in atmospheric surface pressure indicate change in weather and this weather factor is used during an ongoing wildfire to help warn of weather changes. Atmospheric stability is a weather factor that firefighters are trained to be aware of due to how it can influence wildfire spread and intensity, with, for example, a highly unstable atmosphere conducive to erratic fire spread directions. Fuel dryness is an important factor affecting wildfire behaviour because of the significant variability in fuel moisture content over time and space. The moisture content of fine dead fuels - the fuel component where wildfires start and spread, can vary on a daily and hourly basis compared to large woody fuel moisture which may vary over weeks or live fuel that only changes seasonally or during times of significant moisture stress (i.e. prolonged drought). Rate of spread is an important fire behaviour characteristic because it contributes to the size and speed of a wildfire and the potential intensity and flame length, as well as to the resources required to contain and extinguish it.

The low frequency of natural (lightning) ignitions in New Zealand is a combination of New Zealand's maritime climate and the lightning, particularly dry lightning – lightning that occurs without heavy rains (Etherington and Perry, 2017). The temperate maritime climate is a result of the surrounding Pacific and Southern oceans and Tasman Sea, which results in weather systems with high moisture content and regular rainfall. Sitting in the mid-latitudes, New Zealand experiences a myriad of airmasses that create complex patterns of highs, lows and frontal boundaries that pass over its islands on a frequent basis. Even dry airmasses originating over

Australia or Antarctica often pick up moisture as they move towards New Zealand. In general, this translates to shorter periods of dry conditions and wildfires that are uncontained and active for days rather than weeks, as compared to the more fire-prone continental land masses (where wildfires may last months and burns tens of thousands to millions of hectares). If, however, the air masses move quickly over the ocean (e.g. a dry cold front from the south), they remain dry, and this can accelerate fire spread.

Climatically the El Niño Southern Oscillation (ENSO) accounts for approximately a quarter of New Zealand's seasonal variance when these events occur, explaining part of the year-to-year variability in fire danger in different parts of the country (Pearce & Clifford, 2008; Pearce et al., 2007). La Niña tends to bring warmer temperatures and increased rainfall in the northeast of the country and lower rainfall in the southwest. With El Niño, the southern and western parts of the country experience increased rainfall, while the eastern and northern parts receive less. Maps of New Zealand's wildfire seasonal severity demonstrate the complexity of fire season severity and that global climate cycles (e.g. El Niño) only account for a portion of the variability (Clifford, 2024).

Synoptic scale weather systems (large weather patterns at 1000 km to 2500 km across) bring shifts in drying/wetting conditions that immediately affect the readiness of fine fuels (grasses, small woody material, and litter) for ignition – conditions can change in a matter of seconds to minutes with changes in the atmospheric moisture content. A rapid decrease in relative humidity is a watch-out condition during wildfires as it may lead to extreme wildfire behaviour as fine fuels become drier and more available for ignition. Forests planted in areas where sudden and rapid relative humidity decreases are likely are then therefore susceptible to an increased likelihood of ignition and rapid-fire spread. Medium and large woody fuels do not dry out as rapidly, with ignition susceptibility linked to longer drying periods or drought that allow for drying of the deep organic layers, duff, and medium and large woody logs, as well as live vegetation. A deep-seated drought is a known precursor to extreme wildfire behaviour, as demonstrated during the 2018 California extreme wildfire season (Brown et al., 2020) and the 19/20 Black Summer wildfires (Nolan et al., 2019). Deep-seated drought will dry both the surface fuels as well as the live fuels (grasses, scrub, and forest vegetation) increasing the fuel readily available for ignition. When evaluating the impacts of drought and fire, it is important to understand the conditions prior to a drought. While periods of rain reduce the potential for ignition, if these periods of rain are in the spring and cause rapid vegetation growth, this can lead to an increase in fuels available for burning during summer.

In addition to synoptic scale drying/wetting conditions, it is important to recognize geographically important seasonal conditions that dry out fuels, increasing wildfire hazard. 'Frost curing' is used in New Zealand to describe the effect of spring dip on the grasses in the McKenzie Country. Spring dip refers to when the plants have yet to awaken from dormancy, yet there is no snow cover. During spring dip foliar moisture is low, resulting in a large amount dead fuel available for ignition (Jolly et al., 2014; Tymstra et al. 2021). This is most prominent in inland areas, such as the Mackenzie basin, which has experienced three wildfires in early spring (near Lake Pukaki and Lake Ohau), where the frost-cured fine fuels (grass and litter) carried the wildfire into forest vegetation. The local communities and Fire Emergency New Zealand are highly tuned to this unusual fire risk as under the right conditions, trees, scrub, and grass can all burn at any time of the year.

Wind speed and wind direction are often the most important factors directly related to the rate of wildfire spread. Changes in wind speed and direction can occur quickly with incoming weather fronts or with onset of foehn winds or slope and valley flows. Terrain and canopy type (i.e. closed or open) can further influence the wind direction and speed. For example, a forest canopy can drag and slow wind speed, depending on forest type and number of gaps in the canopy structure. In general, wind speed is related to seasonal changes in the temperature difference between the equator and poles with the strongest winds occurring in the spring and the lightest winds in the autumn. In the shorter term, persistent windy conditions, particularly those associated with a dry atmosphere, such as the northwesterly winds Canterbury experiences, will rapidly ready the fuel for ignition. Dry winds help to evaporate moisture from fuels and to accelerate wildfire spread, and this increases the likelihood of wildfire ignitions and creates wildfires that are difficult for emergency response to contain and put out. In New Zealand the topographic locations where these types of winds occur regularly are known (i.e. Canterbury Plains, Hawkes Bay, Wairarapa) and forests planted in these zones will be subject to a higher frequency of conditions ready for ignition (Simpson et al., 2014).

When weather and climate conditions align, the entire country can experience high to extreme fire severity risk (for example in 2012-2013), which happens most years in Otago, Canterbury, Marlborough and Hawkes Bay/Wairarapa (Clifford, 2024). Currently the New Zealand wildfire season is considered to occur between October through April. Global trends demonstrate that wildfires are occurring earlier in spring and extending later into autumn, which is also becoming apparent in New Zealand. The regular occurrence of late winter and spring wildfires in the Mackenzie district is a manifestation of this in the context of New Zealand's unique combination of terrain, weather, and environment. For example, in parts of the United States an effort has been made to eliminate the phrase 'fire season' from public notices as the wildfire risk now runs nearly all year.

According to the Fifth Assessment Report of the IPCC, the magnitude and frequency of natural disturbance events (e.g. fires, outbreaks of insects and disease, floods) are expected to increase due to the predicted warming climate (Seidl et al., 2011). Climate change is predicted to substantially increase the wildfire risk worldwide, placing many regions at risk of increased fire frequency and severity throughout the year (Seidl et al., 2011). In New Zealand, research consistently suggests that there will be an increase in the number of days of wildfire danger in the very high and extreme risk categories because of an increased potential for drought, drier and windier conditions, and an increased frequency of thunderstorms all of which lead to greater fuel availability, and a longer fire season (Melia et al., 2022; Pearce et al., 2008a; Pearce et al., 2011; Pearce et al., 2005; Watt et al., 2019).

Climate modelling for the entire twenty first century by Melia et al. (2022) suggests that New Zealand has already experienced the very extreme wildfire weather conditions that aligned to produce the Australian Black Summers of 2019/2020 (globally considered the worst wildfire season due to the length of burning), and that the frequency of occurrence of these conditions will continue to increase. The Melia et al. (2022) model results demonstrate that extreme wildfire days will occur under multiple emission scenarios, and that we have entered the realm of RCP2.6 (Representative Concentration Pathway, radiative forcing at 2.6 W/m^2 in the year 2100) emission scenario with our current wildfire hazard. This hazard may be more due to predicted weather patterns rather than emissions themselves (Melia et al., 2022).

New Zealand is on a similar wildfire trend to the rest of the world, in that wildfire intensity, severity, and frequency all predicted to increase with the warming climate (Cunningham et al., 2024; Tollefson (2024)) l. Longer, or even continuous fire 'seasons' can be expected. Australia, New Zealand's wildfire prone neighbour, is the proverbial canary in the coal-mine that illustrates to the rest of the world where they are potentially heading. While New Zealand lags behind other around the world due to our maritime climate, indications from the UK, Mediterranean and other parts of the world, as well as climate change impacts modelling undertaken for New Zealand (Melia et al., 2022; Pearce et al., 2011; Pearce et al., 2005; Watt et al., 2019) suggest across New Zealand we can expect an increase in number of days of increased fire risk. This increase in number of days is a concern, because the longer the region is in high risk, the more likely human activity will trigger an ignition. Regionally, the number of days of wildfire risk will be greatest along the east coast of the North Island (particularly around Napier), Central Otago, Canterbury and Marlborough with future climate projections suggesting a greater number of very high and extreme wildfire risk days as compared to other regions (Melia et al., 2022; Watt et al., 2019). It is important to recognise that under the right weather conditions, such as those described here, any vegetation can burn, even land cover types that are typically thought of as having a low fire hazard such as old growth native forests.

How forest structure influences fire behaviour and spread

From early establishment of a forest through to its maturity, changes in key vegetation (fuel) characteristics occur over time and space (the landscape). In addition to stand age, management practices (e.g. silvicultural treatments, pruning and thinning, stocking rates, passive management) and disturbance (e.g. fire, flood, wind, snow, frost, prolonged drought, chemical sprays, fungi and insect attack) also influence fuel characteristics over time and space. Site conditions and climate may also affect the presence of understory species and rates of decomposition of fallen dead material or silvicultural wastes. Wildfire hazard will vary (yearly, seasonally and day to day) as a function of changes in fuel moisture content and condition, which is related to changes in climate and weather conditions. The drier the fuel, the more is available to burn (easier to ignite and be consumed in a fire). These changes impact how easy it is for a wildfire to start, spread and do damage.

Physical fuel characteristics and the interaction of these are central to influencing fire behaviour (Werth et al., 2016). Differences in fuel type, quantity, and location can significantly change fire behaviour in otherwise similar live fuels. The fuel characteristics that are used to describe fuel types and their contribution to the ease of ignition, flammability (especially of live foliage) and fire spread potential include:

- Horizontal and vertical fuel structure. Horizontal continuity affects the spread of a fire across a landscape, while vertical continuity influences if a fire can transition from the surface to the canopy (Figure 7). For example, the presence of ladder fuels aid spread of a surface fire into the canopy to become a crown fire. Horizontal and vertical structure is influenced by:
  - Age class or seral stage (Table 1, Figure 8).
  - Vegetation composition of both understory and overstory species.
  - Stand structure (cover and density (spacing), height, height to live crown, crown ratio, stand maturity, horizontal and vertical continuity).
- Surface fuel composition (size and shape) and loading. If fuels are dry then higher fuel loads translate to a higher fire intensity, however fuels are not always dry and therefore are not available to burn. The surface area to volume ratio affects how quickly fuels gain and lose moisture, meaning different fuels in the same location may become ready to burn while others are unavailable. Smaller fuels gain and lose moisture more rapidly than larger fuels. Tightly compacted surface fuels may struggle to burn due to lack of oxygen, while well-spaced fuels receive the perfect balance of heat and oxygen for efficient combustion (Schwilk, 2015).
- Fuel moisture (live fuel moisture, dead fuel moisture, and dead to live ratios). Fuel availability and resulting fire intensity is influenced by the moisture content of fuels and the amount of fuel. Dead fuels of any species tend to be more likely to burn as compared to live fuels (e.g. Dent et al. 2019).
- Chemical composition. Chemical composition can vary the fuel's susceptibility to ignite, which is influenced by vegetation type and time of year.

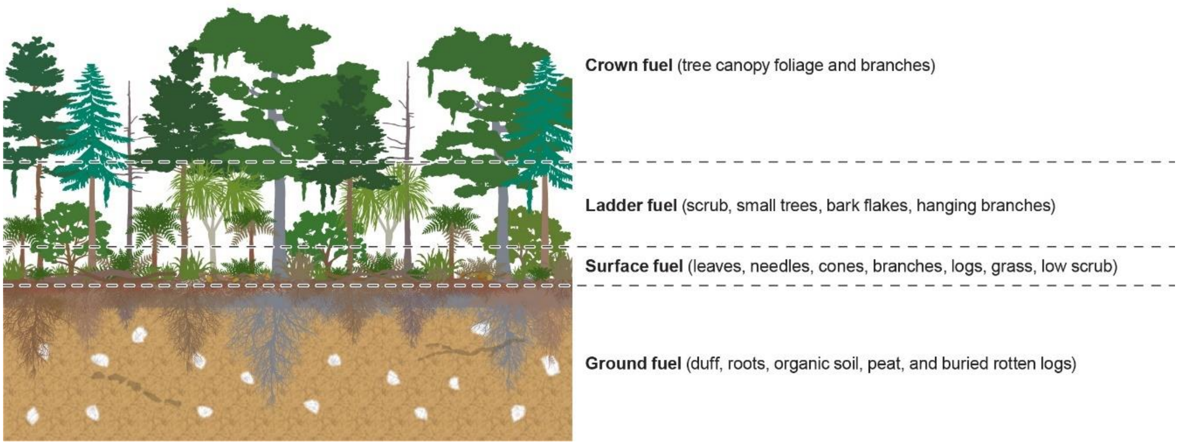

Figure 7. Vertical arrangement of fuels (fuel layer). Graphic Design Credit: Dale Corbett, Scion.

To capture the temporal and spatial variability in forest fuels and thus wildfire hazard, it is important to consider the forest stand context. Forest succession, starting from early establishment through to maturity, has been grouped into seral stages based on the similarities of unique fuel characteristics that influence how a fire behaves (Table 1, Figure 8). For each seral stage, potential fire behaviour is based on available fuel loads (AFL), rates of spread (ROS), head fire intensity (HFI), and extreme fire behaviour (Table 1, Figure 8).

There are multiple forest types in New Zealand, fuel and fire behaviour models have not been developed for many of these as most fuel models are focused on radiata pine [*Pinus radiata* D.Don]. Therefore, we describe wildfire hazard and risk by seral stage rather than forest type. However, when species information is available, that is woven into the description of wildfire hazard and risk. Some of the forests in New Zealand are managed to maximise target benefits (e.g. wood harvest, carbon credits), using a variety of silvicultural techniques (e.g. thinning, planting, pruning). The range of forest types that are present in New Zealand, include (adapted from Wakelin et al. (2023)):

- Managed commercial forests of exotic species (e.g. radiata pine, Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], Cypresses, Redwood, *Eucalyptus*, other soft and hard wood species). These have varying management strategies (e.g. thinning timing and intensity, rotational age, continuous cover).
- Transitional forests from exotic to native species. These can occur with managed or unmanaged transition, and with or without salvage and harvest extraction.
- Managed and unmanaged native forests of different ages and either mixed or single species (e.g. podocarp, beech, mānuka/kānuka, kauri).
- Unmanaged wilding conifer forests.

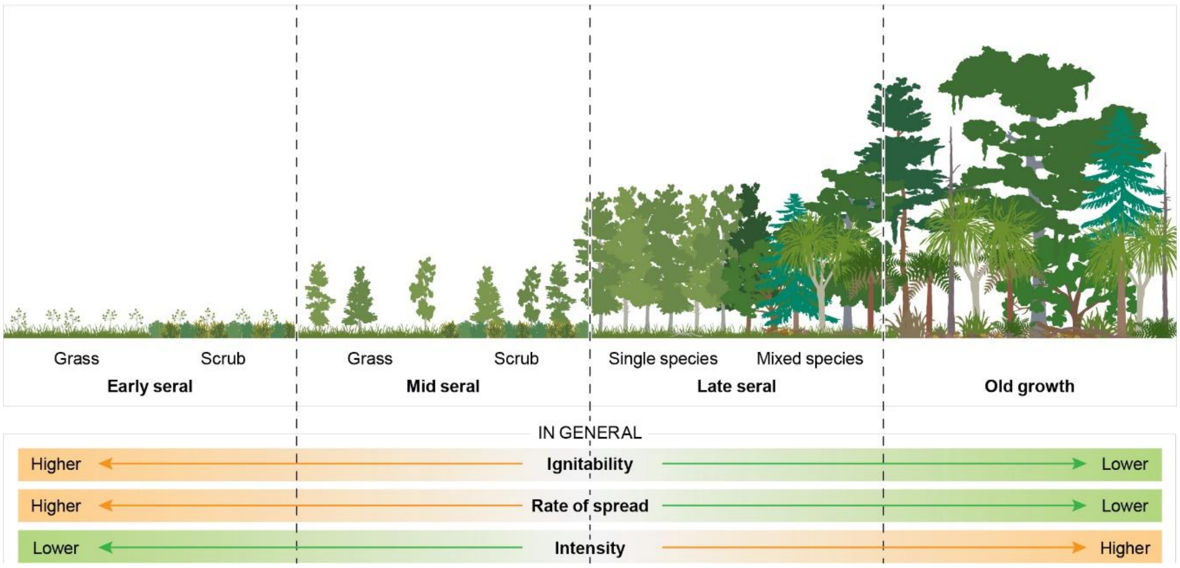

Figure 8. Seral stages found within New Zealand Forests, highlighting native forest species. General fire behaviour is displayed using arrows representing lower to higher ignitability, rate of spread, and intensity. These are general because the realized fire behaviour will be dependent on landscape context, weather, and species composition and structure. Graphic Design Credit: Dale Corbett, Scion.

Fuel and fire behaviour models developed in Clifford et al. (2013a) and Pearce et al. (2012) remain the best state of knowledge to date and are based on experimental burns in the field, wildfire observations, international models modified for the New Zealand wildfire environment, and expert opinion. These models still require further development and calibration, especially given the changes in silvicultural management practices over the last 30 years (e.g. plantation forests are now left unpruned and un-thinned and have higher stocking rates than what current fuel models incorporate). Also, there is a growing popularity with planting species other than radiata pine (such as eucalypts, Douglas-fir, mānuka and native forests). There is also an increasing trend of using scrub, such as gorse, or conifers (wilding or planted) as a nurse canopy for providing shade and microclimate conditions to aid re-establishment of native New Zealand tree species (Wilson 1994).

Current New Zealand models have shown underpredictions for rates of spread and intensities during some wildfires in new and emerging fuel types, such as wildings (Clifford & Pearce, 2009; Clifford et al., 2013b). For example, wilding pines are currently lumped into the Radiata pine plantation model. However, forest structure in unmanaged wilding pine forests are different (greater horizontal and vertical continuity) compared to managed plantation forests, where trees are pruned and thinned. These structural differences lead to the potential rate of spread and intensity being greater in wildings, especially in times of drought.

In describing wildfire hazard and potential fire behaviour for forest succession in this paper, the following assumptions have been incorporated:

- Fire behaviour is presented based on how a fire would start and spread in warm dry and windy conditions.
- Each seral stage is described using the central point in time. This is because there is variability in fuel arrangement and height during forest succession over each seral stage.
- Fire behaviour descriptions are focused on seral stages and fuel structure, rather than species. This is because fuel models are not available for all species and age combinations. The best available information on individual species flammability can be found in Appendix 1, however it is important to understand the limitations with the flammability rankings as identified in the appendix.
- Estimates of fire hazard were done by assuming that the height of native vegetation increases over time, and thus available fuel also increases.
- Naturally regenerating forests are typically found in regions and locations that have higher rainfall, so they are typically harder to ignite, except when there is prolonged heat, wind and/or drought.

These caveats are important to consider when interpreting wildfire hazard and potential fire behaviour:

- **There can be unique situations that are potentially dangerous at any level of fire danger.**
- Fire behaviour can change rapidly with changes in fuel conditions, slope and exposure to wind, and no model can ever fully account for all the variables that affect fire behaviour.
- Day to day and seasonal variations in fuel hazard also occur that can either inhibit or exacerbate a fire's behaviour.
- Not all vegetation present within a fuel type is available to burn over a season and during day-to-day weather conditions.

Early Seral Forest - Fire Hazard and Potential Fire Behaviour

Early seral stands establish following natural or anthropogenic disturbance. In New Zealand, many early seral stands occur in previously farmed areas that may have been originally cleared with fire and then left to revert to native forest cover over time either naturally (regeneration) or with human assistance (afforestation). Early seral forests have simple well defined and low-stature fuel layers (less diverse) with or without broken fuel continuity (bare earth). Early seral vegetation that typically colonizes bare earth include grass species (Figure 9), as well as pioneering exotic (e.g. gorse, broom) and native scrub species (e.g. bracken, mānuka, kānuka) (Figure 10).

In early seral stands most of the vegetation is exposed to the weather elements (solar radiation and wind) where fuel moisture contents can change rapidly with weather conditions, which increases the number of days where ignition potential is higher. The wildfire season in New Zealand generally spans from October to March, but grass and scrub fuels have a wider wildfire season window, drying out first in the wildfire season and becoming a hazard earlier than a mature forest will. These sites can remain hazardous over much of the wildfire season and even into winter or early spring (under snow/frost curing or prolonged drought conditions). Therefore, early successional vegetation (Grasslands and Scrublands) is much more flammable and hazardous compared to mature late successional forest vegetation (Perry et al., 2015).

Grass with tree seedlings

Fire hazard and behaviour of grasslands is influenced by the time of the year, type of grass (annual or perennial), species composition, absence/presence of grazing or mowing, and fuel moisture (how dry/cured). Grass fires are typically less intense and shorter-lived than forest fires, however they ignite easily and can spread fast. Of all the fuel types, fires can travel the fastest in these light flashy fuels. The highest rates of spread occur when grass is fully cured (dried out) and under dry and windy conditions. Fires in taller and more continuous grass covers (rank, ungrazed pasture or tussock) are more intense than those shorter in stature (grazed) due to higher fuel loads. There can be significant risk of higher intensities following periods of good growth associated with warm, wet pre-season conditions in spring and early summer once these elevated fuel loads die-off and dry out (cure). Grazing typically results in less dead material building up (thatch), so that these areas have smaller flame lengths and lower intensity fires compared to tall ungrazed locations.

Figure 9. Example of early seral forest - grass with tree seedlings. Photo credit: Selwyn Plantation Board.

Pioneering scrub species with tree seedlings

Scrub fires differ from forest and grassland fires due to the ability for the fire to rapidly develop into a comparatively much higher intensity under the same conditions. This is where the species composition is important because some scrub species have higher ignition potential and are more of a hazard due to the presence of chemical compounds in the foliage, and/or flaky bark, and/or the ability for dead litter to build up in the crown (especially gorse [*Ulex europaeus* L., mānuka [*Leptospermum scoparium* JR Forst & G. Forst], and kānuka [*Kunzea* spp.]). This is in comparison to lower flammability pioneering scrub plants that have reduced fire ignition potential and subsequent fire. Not all scrub species have a high wildfire hazard, for example broom [*Cytisus scoparius* (L.) Link] is often hard to ignite and does not burn at as high of intensities as gorse or mānuka (Appendix 1).

Figure 10. Example of early seral forest – 3-year-old pine tree seedlings with gorse, Pigeon Valley. Photo credit: Veronica Clifford, Scion

Mid Seral Forest - Fire Hazard and Potential Fire Behaviour

These sites are represented by the transition from an open to closed stand of young trees and saplings with an understory of grass or scrub. Grass or scrub understory remains the dominant vegetation cover and the main fuel type carrying a wildfire until the tree canopy closes (late seral) and the grass and understory vegetation dies out or transitions into later stage successional species. Mid-seral stands are dominated by understory light tolerant vegetation species (with no grazing pressure or weed controls) with fine dead material building up on the ground surface as well as being suspended within the mid-story on tree branches (Figure 11). The density of regenerating or planted tree species will have an impact on when tree canopy closure occurs, and grass or scrub understory cover die out. It can take about 10 (in radiata pine plantations) to 30+ years for gorse to be over-topped by tree species and scrub stems to collapse and decay (Lee et al. 1986; Carswell et al. 2013; Holdaway et al. 2018; Clifford et al 2013). With radiata pine forests, tree canopy closure generally occurs much faster, depending on site location, stocking, and silvicultural treatments. In comparison, canopy closure of young to mature native forests can take several decades or longer depending on species and site conditions (Tepley et al. 2016). These sites may contain residual woody debris from previous harvesting operations or from silvicultural management (pruning and thinning activities). This increase in biomass can contribute to higher available fuel loads and higher intensity fires compared to early seral stage stands. In addition, the taller height of woody scrub understory vegetation (2 – 5+ m in height) results in higher flame heights and fire intensities compared to the early seral stage. Unpruned and un-thinned trees provide ladder fuels (Figure 7) that can aid the spread of fire into tree crowns, which usually manifests as torching of individual trees or discontinuous crowning (intermittent crown fire) in these forest stands as the fire moves between the understory fuel (grass or scrub) and the overstory of non-continuous tree fuel.

Figure 11. Mid-seral forest. Left: grassland transitioning into a young forest. Photo credit: Selwyn Plantation Board. Right: 2-meter-tall broom with 6-year-old pine trees, Bottle Lake Forest. Photo credit: Veronica Clifford, Scion.

Late Seral Forest - Fire Hazard and Potential Fire Behaviour

Determining fuel hazard and subsequent fire behaviour in young and mature forests becomes complex with forest age and depends largely on the forest species present, the forest structure (which is influenced by silvicultural treatments (or lack of) and/or other disturbances) and other site factors relating to terrain and weather. Structural factors that begin to change with forest age include increased fuel height, fuel cover, and total biomass across all fuel layers (ground, surface, ladder, and crown; Figure 7). Typically, there is an increase in litter on the surface (forest floor), and deep organic duff (humus layers) building up as the litter, roots and any fine and coarse woody debris material decomposes over time.

The forest floor surface layer is the main fuel layer carrying a wildfire. The replacement of grasslands or scrub into mature forest stands shifts most fires from fast moving to slow moving surface fires of lower intensity because solar radiation and wind are reduced in a forest environment and forest floors are generally cooler and moist for longer periods of time over the season (e.g. Beech forest - Tepley et al. 2016). Clifford et al. (2013b) showed that fire hazard in older wilding stands was lower than the tussock/grassland ecosystems they replaced because of higher moisture content and lower rates of spread. However, under the right weather conditions, a wildfire can move through a closed canopy forest with varying intensities and speed depending on its structure and the accumulation of biomass and availability of fuels to burn. In closed forests, the concentration of woody fuels building up with interconnecting crowns creates a hazardous potential for high fire intensity, large flame lengths, crown fires and spotting.

Forest and fuel structure and the accumulation of biomass is further variable when comparing monoculture forests (simple species) with mixed species forest types. In general, native forests are considered less flammable in comparison to exotic plantations. Observations from past wildfires under mild to moderate fire danger conditions are that fires burning into native areas become low intensity and eventually halt the spread by burning a short distance into the forest edge. The reduction in intensity as the fire burns into native forests is likely due to the edge effect where the forest fuels are drier for the first few meters, and/or fuels have been preheated due to a high intensity flame front at the forest edge.

However, in times of drought and extreme fire weather, fuel moisture content declines further and results in more forest fuels available to burn in both native and exotic forests. During extreme drought (prolonged dry conditions) where rainfall is below normal, and in combination with hot, dry windy weather, forests can become drier than normal, allowing all fuels (all types and size classes) in the vegetation complex to become available to burn during a fire. When these conditions occur, surface fires can spread faster and can more easily transition into a crown fire that burns at medium to high intensities. Under prolonged drought, deep seated burning in stump and root structures or buried woody debris (at depths up to 1 m) can result in difficult and prolonged suppression.

In windy conditions, the potential for spot fires also increases. Medium to long range spotting can occur (depending on the fuel type involved and receptive fuel bed ahead of the fire), typically ranging from 500 m to several kilometres in distance, increasing the area burned due to new fires. In New Zealand, anecdotal reports identify spotting may have occurred at 4.5 km from a pine forest wildfire. While the 2015 Onamalutu forest fire a spot fire 2-3 km from the main fire was captured in video. Fuel types that have a chemical composition that increases flammability (e.g. high levels of monoterpenes and sesquiterpenes (Guerrero et al. 2021)) or bark morphology ((Cruz et al. 2012) e.g. flaky bark or stringy back in Eucalyptus species or mānuka) can exhibit higher intensity crown fires and/or longer-range spot fires.

Single species forests (monocultures)

Some forest stands are relatively structurally simple with well-defined surface and crown layers. This includes monocultures of radiata pine and many native beech forests (the succession into native beech forests tends to have lower species richness compared to native mixed species podocarp/broadleaf forests). As a result, these areas can have little to no understory fuels present. Typically, in these forests there is a continuous litter layer on the forest floor, with deep decomposing organic duff layers which will be the primary carrier of fire (Figure 12). Crown fires may initiate under extreme conditions in areas of more continuous ladder fuels (un-thinned exotics, or thickets of young beech saplings).

Figure 12. Late seral single species forests. Top: Mature pine forest, Eyrewell. Photo credit: Scion Research. Bottom: Beech forests. Left: Arthur’s Pass, Photo Credit: Veronica Clifford, Scion; Right: Craigieburn, Photo Credit: Nick Ledgard.

Mixed species

In contrast, natural regenerating forests or those planted in mixed species combinations, tend to have higher species richness, leading to a more heterogeneous forest structure, with mixed ages of fuels, and variable heights of surface, ladder, and crown layers. This heterogeneity leads to differences in microclimates which supports variability in available fuel loadings and fuel moisture (Figure 13). An understory of dense shade tolerant and fire intolerant species can result in a reduction in the ease of ignition, fire spread and damage, especially in older mature forests. However, during significant drought, the higher amounts of litter and other surface fuels combined with ladder fuels (vertical continuity) spanning the surface to the canopy, can result in sustained spread and torching of trees and crown fires if a fire was able to start and spread.

Figure 13. Late seral mixed species forest. Lords Bush, Canterbury. Photo credit: Veronica Clifford, Scion

Old-Growth Forest - Fire Hazard and Potential Fire Behaviour

Prior to human settlement, natural disturbances, particularly large, infrequent geological and geomorphic events such as volcanic eruptions, earthquakes, and landslides were the primary agent to ecological state changes in New Zealand’s forests. Thus, forests were not subjected to long periods between disturbance and therefore it is conceivable that many forests reached climax states. With the arrival of humans, beginning with the Māori around 1250–1300 CE and later with the arrival of European settlers in the 19th century, the nature and frequency of disturbances changed dramatically. Forests were extensively cleared for agriculture, settlements, timber and other uses, leading to a significant reduction in forest cover. Old growth forests were intensively and selectively cleared for the high-grade timber. The use of fire as a tool for clearing land and later as part of pastoral management further increased the frequency and intensity of disturbances, altering the landscape and shifting ecosystem dynamics.

Old growth forests (e.g. Beech Forest and Podocarp/Broadleaf forests) have a diverse forest structure with multiple age and stage classes throughout. Gaps develop within the canopy allowing light to reach the forest floor and reducing canopy continuity. Understory vegetation is well established or regenerating in gaps. In old growth forests, there are deep organic surface and ground fuels, an abundance of decaying and undecayed branches, logs, and snags contributing to high surface fuel loading (Figure 14). These fuels are usually hard to ignite due to high moisture content, however during drought when they do ignite, they contribute to deep seated fires, that are devastating to fire sensitive species and require prolonged mop-up by fire-fighters.

Areas of the landscape that have variability in fuel continuity and structure are likely to contribute to comparatively slow spread rates, intensities, and a much lower likelihood of intermittent crown fires in comparison to the young and mature forest successional stages above. Rates of spread and subsequent intensities are also expected to be considerably lower than those predicted by current available forest fuel models however, this is a knowledge gap where fuel and fire behaviour models have not been developed for native forest stages.

Figure 14. Old-growth podocarp forest from inside (left) and from the outside (right). Peel Forest. Photo credit: Veronica Clifford, Scion

Table 1. Summarized changes of fire hazard and potential fire behaviour (rate of spread – ROS, intensity, and extreme fire behaviour). For individual species flammability information see Appendix 1.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour

Early seral
 	
Grass with tree seedlings.
 	
Examples: young pine plantations (<5 y.o.), sparse young wilding seedlings, young plantings of other native and exotic tree species, young regenerating native seedlings amongst grass
	• Pasture grass and/or native tussock is the dominant fuel type carrying fire.
	• Open fuel types exposed to weather elements (solar radiation and wind).
	• Fine flashy fuels that can dry rapidly and are receptive to changes in weather.
	• Condition (degree of curing), height and continuity of the fuel affects fuel loads and fire behaviour.
	• Fuel condition varies depending on species phenology, time of the year, and weather.
	• Low biomass (compared to other seral stages), but high AFL (if fully cured).
	  ○ Grazed Grass AFL: 0.2 - 6.8 t/ha
	  ○ Ungrazed Grass AFL: 0.9 - 11.7 t/ha
	  ○ Grazed Tussock: 2 – 23 t/ha
	  ○ Ungrazed Tussock: 3.9 – 43 t/ha
	• Vulnerable to ignition over a wider fire season window compared to other seral stages.
	• People with equipment and vehicles on site can be a source of ignition and increase the risk of a wildfire occurring (with dry windy fire weather conditions).
		Grassfire	A wind driven surface fire can travel fast when the grass is fully cured, there are high wind speeds and continuous grass cover.
			
			Spread rates can typically reach up to 10 km/h but can exceed 12 km/h. [4]
				Surface fuel consumptions only.
				
				Smaller stature vegetation (up to 1-1.5 m tall).
				
				Relatively low flame length (2 – 4 m).
				
				Fuel is consumed quickly within 5- 10 seconds.
				
				Under very dry conditions smouldering ground fires can occur (fire in the root layer).
				
				Intensities range between 1500 – 15,000 kW/m [2,5].
					Rapid rates of spread.
					
					All things equal, a wildfire burning in grass fuels typically has faster rates of spread compared to any stage, including a mature forest.
					
					Very responsive to changes in wind speed and direction, resulting in flank fires becoming larger head fires with a change in wind direction.

Early seral Pioneering scrub species (mānuka, kānuka, gorse,	• Scrub is the dominant fuel type carrying fire. • Open fuel types exposed to weather elements (solar radiation and wind), including grasses and elevated dead scrub fine fuels.	Scrub fire	A wind driven surface fire with low to moderate speeds in comparison to other fuel types.	Surface fuel consumption only. Taller stature vegetation in	High intensity fires with potential short-range spotting (< 500 m).

[4] Using the Ungrazed Pasture model, 100% Degree of curing and ISI of 70.
[5] Assuming rates of spread of 5 km/h and maximum fuel loads of 5 t/ha (grazed grass) and 23 t/ha (grazed tussock). This does not include ungrazed tussock, which could have flame lengths up to 12 meters and intensities up to 50,000 kW/m.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour
broom) with tree seedlings. Examples: young plantations of radiata pine and other exotics (< 5 y.o.), sparse young wildings amongst scrub, young regenerating natives amongst scrub	• AFL in scrublands are considered low to moderate in comparison to other fuel types and will vary with age [6]. o gorse AFL: 40.3 t/ha o mānuka/kānuka AFL: 23.4 t/ha o hardwoods AFL: 15.7 t/ha • Some scrub species are low flammability and difficult for a fire to start and spread (broom) • Gorse, bracken, mānuka and kānuka are highly flammable species (due to the presence of chemical compounds in their leaves, fine foliage and/or retention of dead material). Their presence on the landscape represents a significant hazard.		Can develop rapidly (highly flammable species), very responsive to wind speed. Spread rates can reach up to 5 km/h [7].	comparison to the grass seral stage (up to 6 m). Can generate flame lengths between 10 – 16 m. Intensities range between 37,500 – 100,000 kW/m[8].	Scrub differs from forest and grasslands due to the ability for fires to rapidly develop into high intensity fires. This can occur under conditions that would not normally produce high intensity fire behaviour in forest and grassland fuels.
Mid seral Transition into a young forest with grass understory. Examples: 5-15 y.o pine plantation, mid-age scattered wilding stands, mid-age regenerating natives with grass understory	• Tree crowns extend to the surface but do not create a continuous canopy cover. • Early seral species are transitioning into other shade tolerant species and small trees. • Open tree canopies allow for more light and a warm dry microclimate. This results in drier fuels compared to a closed forest. • Grass remains the dominant fuel type carrying the fire. • Ungrazed grass can reach heights of 1m with thick thatch layers building up adding significantly to the fuel loading. o Grazed Grass AFL: 0.2 - 6.8 t/ha o Ungrazed Grass AFL: 0.9 - 11.7 t/ha o Grazed Tussock AFL: 2 – 23 t/ha o Ungrazed Tussock AFL: 3.9 – 43 t/ha	Grass fire	A wind driven surface fire. May exceed 10 km/h (in fully cured grass under warm windy conditions) [9]. Presence of trees either in low density or in denser open forests reduce wind speed and resulting ROS and therefore are less than that of early seral	Surface fuel consumption only. Smaller stature grass vegetation with higher fuel load (in areas of increased thatch slash) results in higher intensities compared to the early grassland stands. The presence of taller trees adds to the available surface	Intermittent crowning (or torching) of individual trees or small groups of trees is likely, especially in unpruned and un-thinned forest stands that provide ladder fuels aiding the spread of fire into tree crowns. The presence of trees increases the occurrence of short-range spotting (< 500m).

[6] Using a gorse, mānuka/kānuka or Hardwoods model to calculate AFL, and assuming a scrub height of 2.5 m.
[7] Using the gorse/mānuka/kānuka Scrub model and ISI of 70.
[8] Assuming worst case rates of spread (5 km/h) and max fuel load of either 15 t/ha (hardwoods) or 40 t/ha (gorse) for scrub species 2.5 m tall.
[9] Using Ungrazed Pasture model with a height of 0.8 m and 100% cover.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour
	• The presence of trees can contribute to increasing the biomass in the form of leaf litter and elevated fine fuels. • Depending on site treatments there can be a buildup of woody debris and rank grass contributing to higher fuel loading. • People with equipment and vehicles on site can be a source of ignition and increase the risk of a wildfire occurring (with dry windy fire weather conditions).		grassland dominated areas.	fuel load and can sporadically increase the resulting intensity and flame lengths compared to the early seral stage. Intensities range between 12,500 – 50,000 kW/m [2,10].	

Mid seral
 	
Transition into a young forest with scrub understory.
 	
Examples: 5-15 y.o. pine plantation, mid-age wildings (5-15 y.o.), regenerating natives with scrub understory
	• Tree crowns extend to the surface with a dense cover of taller scrub (gorse/broom) present between trees
	• Scrub remains the dominant fuel type carrying the fire.
	• As scrub fuels becomes denser and taller, the biomass and AFL increases [11].
	  ○ gorse AFL: 59 t/ha
	  ○ mānuka/kānuka AFL: 29.4 t/ha
	  ○ hardwoods AFL: 19.7 t/ha
	• Gorse and mānuka are considered hazardous scrub fuels mostly due to large amounts of dead elevated fine fuel that dries rapidly and the presence of chemical compounds in the foliage that enhance flammability.
	• Tree ferns are a highly flammable species that can contain high amounts of dead fine flashy fuels elevated in the canopy and the base of the plant.
	• Open tree canopies allow for warm dry microclimates and can result in drier fuels
		Scrub fire	A wind driven surface fire.
			
			Spread rates may reach up to 5 km/h [12].
			
			Presence of trees in either low density or in denser open forests will reduce wind speed and resulting ROS and will therefore be less than that of early seral scrub dominated areas.
				Live and dead fuels on shrubs and trees can create moderate to high intensities.
				
				A wildfire burning in flammable scrub species typically generates higher intensities compared to a surface fire in a closed forest system, due to exposure of weather elements and the enhanced flammability of this fuel type.
				
				Relatively high flames (10-20 m).
					The presence of flammable scrub fuels in the young forest stands allows a wildfire to develop extremely quickly and burn with higher intensities, even under moderate winds.
					
					The presence of trees increases the occurrence of short-range spotting (< 500 m).

[10] Assuming rates of spread of 5 km/h and maximum fuel loads of 5 t/ha (grazed grass) and 23 t/ha (grazed tussock).
[11] Using a gorse, mānuka/kānuka or Hardwoods model to calculate AFL, and assuming a maximum scrub height has reached (5 – 6 m).
[12] Using the gorse/mānuka/kānuka Scrub model and ISI of 70.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour
	compared to a closed forest, but moister than open grass due to denser scrub.			Intensities range between 25,000 – 100,000 kW/m ,[13].	
Late seral Mature forest, Single species. Examples: Mature and immature pine plantations following crown closure, dense wilding stands, beech forest	• Tree crowns overlap, little or no gorse understory due to shading by the overhead tree canopy. • Beech forests mainly consist of one or two species with an open understory or sparse cover of shrubs and ferns. • Pine forests may have woody debris or decaying scrub present. Silvicultural practices undertaken will determine stand characteristics and resulting fuel loads and fire behaviour in each of the fuel layers of a forest (ground, surface, ladder, and crown). • Unmanaged sites will likely have high ladder fuel loading (branches with suspended needles), this combined with high density increases likelihood for the development of crown fire. • High fuel loads due to high density or closed canopy forests maintain high humidity in the understory. • People with equipment, vehicles, and machinery on site for the duration of pruning, thinning and harvesting are a source of ignition and increase the risk of a wildfire occurring within the forest stand (with dry windy fire weather conditions). • Continuous litter and duff layers.	Forest fire	Ground, surface and crown fires can occur. The primary carrier of surface fire is a litter layer. The replacement of grasslands or scrublands into forests will shift from fast moving to slow moving surface fires (as wind is dampened in a closed forest environment and forest floors are generally moist). The surface fire rate of spread is relatively low compared to other forest stage classes and can reach:	In general, native forest vegetation is less flammable due to high moisture, and thus fires are of lower intensity in native versus exotic. For native forests, fires have a greater chance to ignite and spread in beech forests compared to mixed natives because they are typically located in drier locations. Fire intensities range depending on the wind and fuel dryness: • Pine: <30,000 kW/m [17] • Beech: <24,000 kW/m [18]	Chance of deep-seated fires, crowning and spotting. Crown fires and spotting can occur depending on the heat/intensity generated from the surface fire, height of the crown base height, and terrain steepness. The presence of old scrub fuels, or a lack of pruning and thinning will create ladders, enabling torching and crowning. Deep underground burning in stumps/woody debris and root systems during droughts can create prolonged and difficult mop-up. These areas could smoulder for weeks.

[13] Assuming worst case rates of spread (5km/h) and max fuel load of either 20 t/ha (hardwoods) or 60 t/ha (gorse) for scrub species 2.5 m tall.
[17] Using a max ROS of 2 km/h and AFL of 30 t/ha.
[18] Using a max Ros of 1.2 km/h and AFL of 40 t/ha.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour

	• The presence of dead needles and leaves suspended on lower branches provides ladder fuels that link the surface and crown fuel layers.
	• Beech forests often have a sparse understory cover due to denser canopies and less light reaching the floor.
	• AFL will range depending on the forest species present, density of planting, any management activities undertaken and current weather conditions [14].
	  ○ Pine AFL: 0.4 – 32 t/ha
	  ○ Beech AFL: 0.1 – 38.1 t/ha
	• AFL in beech forests are slightly greater than those of mixed forests for the same build-up index (BUI) value. This is due to generally deeper litter and duff layers that can become available to burn as the forest dries out.
			• Pine: <2 km/h [15]
			• Beech: <1.2 km/h [16]
				If the crowns were involved, flame lengths could be 3 times the height of the forest.	Rates of spread will increase with the presence of crowning and spotting. If crown fire activity is occurring, ROS could be more than two times as fast as the surface fire, due to the canopy exposure to wind and preheating of the crown layer.
					
					Short and medium spotting (up to 2 km in pines, and longer in eucalypts).

Late seral Mature forest, Mixed species. Examples: Mature native forests, including mixed podocarp/ broadleaf and mixed beech/broadleaf	• Canopy closure shelters forest floor and surface fuels from solar radiation and weather, a microclimate forms and can result in cooler and moister conditions. • Canopy closure doesn't end up with death and decay of understory, but a complex mix of shade tolerant species (if following a natural forest successional pathway). • Mixed podocarp/broadleaf forests have high species diversity with a dense understory of ferns, shrubs, vines and trees. These forests are typically located in wet sites and most	Forest fire	Ground, surface and crown fires may occur, although crown fires are rare. Surface fires are fuelled by leaf litter and low growing vegetation. The primary carrier of surface fire is a litter layer with ROS	Surface, ladder, and canopy fuels can be consumed. Typically, many native forest species are low flammability and retain very little dead material on the plant, so would generate lower fire intensities if a fire was to ignite.	For this fuel type, ladder fuels are abundant, but a surface fire needs to be present to support a crown fire, combined with moisture stressed ladder and crown fuels. If experiencing drought conditions, the organic underground layers

[14] Using a range of BUI values of 10 to 120 (BUI can be greater than this) and a Mature Pine model or Beech Forest model.
[15] Using the Mature Pine Forest ROS model, and max ISI and BUI values.
[16] Using the Indigenous Forests ROS model, and max ISI and BUI values.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour
	fuels are unavailable to burn even with a range of low to high biomass present. • AFL will range depending on the forest species present, density of planting, any management activities undertaken, and current and preceding weather conditions (e.g. drought). ○ AFL ranges between 0.4 – 31.8 t/ha [19] ○ Beech AFL: 0.1 – 38.1 t/ha [20]		up to 1.2 km/h (windy, dry conditions).[21]	Surface fires result in removal of litter layers and burning into deep duff layers. Ground fires are fed by roots, duff and other buried organic matter. Intensities generated may reach 18,000 kW/m (under dry windy conditions)[22]	and woody material building up on the floor can become available to burn and result in difficulties in suppression (lengthy mop-up).
Old growth forest Old forest, mixed or single species Example: mature native podocarp/ broadleaf forests	• Old growth forests have a diverse forest structure, with a mixture of understory and overstory canopies of various heights. • Canopy closure shelters forest floor and surface fuels from solar radiation and weather, however gaps can develop within the overstory canopy allowing light to reach the forest floor and reducing canopy continuity and increasing exposer to weather elements. • Snags and fallen trees are present and hung up in the canopy. • Deep organic surface and ground fuels are common, with an abundance of decaying and undecayed branches and logs contributing to high surface fuel loading.	Forest fire	Ground, surface and crown fires may occur, although crown fires are very rare. The ease of ignition may increase with gaps in the canopy and surface fuels exposed to weather elements. Understory fuels responsible for a surface fire are	Many native species, especially broadleaves, are low flammability and retain very little dead material on the plant, so would generate lower fire intensities if a fire was to ignite. Woody debris on the surface can add to the available biomass. The rate of surface fuel drying is dependent on the	The presence of vertical fuel continuity (ladder fuels) creates a bridge from the surface to the canopy for the possibility of crown fires, but an intense surface fire is required, which will only occur under extreme conditions. Gaps in the canopy could result in intermittent crown fires.

[19] Using the Podocarp/Broadleaf forest model and a range of BUI (10 – 120).
[20] Using the Beech forest model and a range of BUI (10 – 120).
[21] Using the Indigenous Forests ROS model, and a range of ISI and BUI values.
[22] Using a ROS of 1.2 km/h and a AFL of 30 t/ha.

Stage	Key variables that influence fire behaviour	Fire type	Rate of Spread (ROS)	Intensity	Extreme Fire Behaviour
	• AFL in Forest fuels types can range from low to high depending on the season. ○ Podocarp/Broadleaf Forest AFL range between 0.4 – 31.8 t/ha [23]		litter, twigs, bark and finer leaves on shrubs and small trees. Spread rates and intensities are assumed to be less than that of a closed mature forest due to a breakdown in vertical and horizontal fuel continuity in the surface and canopy. ROS up to 1.2 km/h (windy, dry conditions).[24]	understory and overstory canopy gaps. Ground fires are fed by roots, duff, and other buried organic matter. However, ground and surface fuels may never dry out until extended drought. There would then be large quantities of fuel available for combustion. Intensities are typically less than 10,000 kW/m.	Expect smouldering and deep-seated fires that could burn for days in very dry conditions.

[23] Using the Podocarp/Broadleaf forest model and a range of BUI (10 – 120).
[24] Using the Indigenous Forests ROS model, and a range of ISI and BUI values.

Landscape Pattern and Wildfire Risk

The fire environment (Figure 5) is responsible for driving ignition susceptibility and fire behaviour at the landscape scale. In many wildfire scenarios, weather is the key factor that drives fire spread (e.g. Fang et al., 2015), while climatic trends (e.g. drought), topography, and fuels (vegetation structure and species) are linked to the fire severity (e.g. Birch et al., 2015; Fang et al., 2015; Prichard & Kennedy, 2014). Wildfires are influenced by a specific combination of synoptic weather conditions combined with local meteorological conditions (Pretorius et al., 2020).

Influence of Topography

Topography is a metric associated with the physical aspects of the landscape, including elevation, slope steepness, slope shape, topographic position, and aspect, which influence biophysical gradients on a site (e.g. solar radiation, micro-and macro site moisture) which in turn drive productivity and species composition (Estes et al., 2021), thus influencing ignition susceptibility and fire behaviour. Topography's most common effects on fire behaviour comes indirectly through its influence on localized weather variables. Elevation and aspect influence temperature and humidity, with warmer temperatures generally at lower elevations and on north aspects. These patterns influence fuel conditions, including fuel moisture, fuel load and availability. Terrain shape can accelerate fires or create unusual spread patterns by influencing wind flow; one example of this is pressure-driven channelling when wind is funnelled up valleys or gullies.

Slope angle changes the physical distance between the flame front and the fuels. When a wildfire moves upslope, fuels are closer to the flame front where they experience increased radiative and convective heating and are ready for ignition faster than they would on flat terrain. This increases the rate of wildfire spread uphill. A general rule of thumb is to double the rate of spread for every increase of slope angle by 10° (Pearce et al., 2012). For downhill spread, the rule of thumb is that the wildfire moves at a slower rate due to the greater distance between the fuels and associated decrease in radiative heat output from the flame front; however, there are cases where this 'rule' can be broken. The 2017 Port Hills wildfire progressed rapidly downslope due to atmospheric conditions dominating the wind flow which drove fire spread (Pretorius et al., 2020). Similarly, during the 2011 Margaret River wildfire, strong downslope winds combined with unusual nighttime drying to create a fast-moving wildfire in coastal scrub with devastating results (Kepert et al., 2012).

Topographic variables can guide planning of landscape level afforestation to minimize wildfire hazard and risk by considering the right place for the right species and forest structure. Topographic variables (i.e. slope shape, aspect, and slope position at both the macro and micro scale) have been used to guide forest restoration treatments in North America (Meyer et al., 2021; North et al., 2009) and at a high level the concepts can be applied to afforestation in New Zealand. This requires consideration of national, regional, and local topographic and climatic patterns. New Zealand's regional distinctions that drive vegetation differences between the North and South Islands and eastern versus western regions have been apparent throughout the Holocene (Newnham et al., 2013). Based on these topographic and climatically driven differences afforestation should be managed differently in these regions, because both the landscape context and the fire risk are different. At the local or stand scale, this could mean that forests with flammable species (e.g. mānuka/kānuka) could be targeted for planting in areas of higher moisture. Redwood, a species known for its fire ignition resistance, for example, are modelled to grow exceptionally well on the North Island where they are more climatically suited, and while they grow in South Island climate zones, i.e., northern Nelson/Marlborough, they are not well suited for Southland where temperatures are colder (Watt et al., 2021).

Role of vegetation

Although the mosaic of vegetation, including the size of forest patches (fuel type and continuity) contributes to wildfire risk. Apart from wildings (Clifford et al., 2013b) there are no quantitative studies from New Zealand looking at how afforestation changes landscape wildfire risk. Clifford et al. (2013b) found that fire hazard for wildings was dynamic depending on the weather, stage of invasion, and past treatment activities. International wildfire simulations can provide some insight into how landscape risk may change. Collins et al. (2015) simulated how woody plant revegetation (primarily Eucalyptus species) in south-eastern Australian pasture lands would change wildfire risk and found that increased biomass does not necessarily mean an increase in wildfire risk but is dependent on the type of vegetation and the landscape context, with fire weather and pasture fuel load being the most important variables linked to fire spread and suppression requirements. They found that an increase in native woody vegetation could decrease fire size and intensity when the area being converted was a moderate to high biomass (4.5 – 7 t ha^{-1}) pasture with high connectivity (Collins et al., 2015).

Change in wildfire hazard and risk is linked to how the landscape changes. Unfortunately, there is uncertainty in the current extent and projected future extent of forests on the landscape (Wakelin et al., 2023). The uncertainty surrounding future forest coverage (extent, locations and types) is also high as it will be influenced by economics, disturbance, and planting/regeneration success. One estimate is that there is an additional 8.4 million ha of land available for conversion to forest and an additional 1 million ha of regenerating native forest on farmland (Wakelin et al., 2023). Going forward there is therefore considerable uncertainty around the future vegetation mosaic at the landscape level.

The vegetation mosaic is especially important with forest patch size and proximity to other land use/vegetation types, such as grasslands (natural or farmed), peatlands or scrub and human activities, all factoring into likelihood of wildfire ignition and spread. Proximity to grasslands is a factor because fine grassland fuel dries easily and becoming available for ignition and can carry fire at a rapid rate. Wildfire simulations, based on historic data, primarily from human caused ignitions, found that wildfires in a tropical forest ecosystem were more frequent in forest patches smaller than 100 ha compared with forest patches larger than 1000 ha. This is because the smaller forest patches had increased solar radiation hitting the forest floor thus increasing the under-canopy temperature and lowering the humidity, resulting in increased fuel drying (Guedes et al., 2020). These results could be translated to New Zealand's late seral native forests as it is well documented that older native forests maintain a moist understory canopy (Kitzberger et al., 2016), which reduces the spread of fire. Thus, as forest patch size decreases, the influence of the tall canopy on fuel moisture also decreases. The tropical forest wildfire simulations also noted that the shape of the patch was an important predictor of fire, as irregular forest shapes led to larger edge effects and reduced interior fuel moisture (Guedes et al., 2020). The smaller forest blocks (<100 ha) with a greater edge-to-interior ratio had a higher risk of ignition from the surrounding landscape – from non-forest land, such as grasslands which have a higher ignition likelihood (Guedes et al., 2020). These patches also had an increased potential for high winds in the forest interior driving the wildfire and drying the fuels (Guedes et al., 2020).

The context of land adjacent to forests is critical as there are ignition risks from the adjacent land as well as within the forest itself. Pearce et al. (2008b) suggest that, based on a survey of exotic forest owners by Cameron et al. (2007b), nearly twice as many fires and six times the area burnt occur outside of forest areas on adjacent land as within forests. In New Zealand the greatest risk of ignition occurring is where there is public access (Gross et al., 2024b). The context of how forests are interspersed with agricultural land influences the wildfire hazard and risk further. For example, based on limited data, current carbon forests[25] in New Zealand are frequently located near farming units and powerlines (Gross et al., 2024b). Power transmission lines carry massive voltage and can cause ignition due to electrical discharge, while farming practices can spark ignition under dry conditions; for example, the Pigeon Valley wildfire (2019) was started by a tractor blade sparking on a rock. Other management practices that have a potential to spark a wildfire are spontaneous combustion of decomposing woody debris piles, and pile burns or prescribed fires which historically have been identified as a dominant cause for wildfires, with grass fuels carrying a much higher risk of ignition as compared to forest fuels (Figure 3).

Wildfire spread

To mitigate wildfire spread, it is important to either slowdown or stop entirely the advancing wildfire. The best way to do this is to introduce 'gaps' in the fuel/vegetation or lower flammability vegetation that takes longer to ignite. One of the hypothesized reasons for fire sizes being smaller in New Zealand compared with many other countries is because of the broken-up landscapes, with complex terrain and highly variable vegetation cover. The largest fires are in areas where there are more continuous fuels, such as high-country tussock and semi-improved grasslands. Ideally forests

[25] Carbon forests in the context of this report were any forest with the ability to earn a reward for carbon sequestration.

should be planted in a way that can interrupt wildfire spread. If fuel is continuous across the landscape and a wildfire does ignite and spread, fuel alone would not change the wildfire's behaviour. If, however, fuels are heterogeneous with patches of different species and stand structure, then the wildfire behaviour would change due to the change in fuels. For example, during a crown fire, if tree canopies are connected (horizontal connectivity of fuel) then a sustained crown fire is likely to occur; if, however, there are gaps in the canopy, then the fire itself may become an intermittent crown fire (with individual tree torching) or surface fire.

Fuel breaks (lower flammability vegetation) and fire breaks (no fuel), herein referred to as fuel breaks, are features on the landscape designed to change fire behaviour and provide opportunities for suppression (Aguilar-Arguello, 2022). Natural and anthropogenic fuel breaks can stop fuel continuity, adding heterogeneity into the stand or landscape. This break in fuel continuity can be a physical gap such as a river, lake, rocky outcrop, road, or can be a change in the fuel, such as a change to broadleaf native scrub with a high moisture content. Palaeoecological records in New Zealand have demonstrated the importance of zones of high rainfall and geographic barriers in preventing large scale landscape wildfires (McWethy et al., 2010). It is important to recognize that the success of fuel breaks, whether natural or human-made, will be linked to fire intensity and potential for spot fires ahead of the main fire as well as where the break is located relative to terrain and its maintenance (Pearce, 2019). The taller the fuel or the greater the fire intensity, the larger a fuel break would need to be to stop or slow the spread of a fire. As a rough rule of thumb, in the absence of ember transfer (spotting), a fuel break needs to be at least 2-3 times as wide as the height of the vegetation, or 1.5-2 times as wide as the flame lengths produced by the fire, to prevent it being breached through flame contact or radiated heat. Since average flame heights (usually equal to or less than flame length) during extreme fire conditions may be up to six metres in grass fuels and between two to three times a forest stand's height (Stocks, 1987; Stocks et al., 2004), this raises considerable challenges in relying on individual fuel breaks without other mitigations. While fuel breaks can slow/change fire behaviour on the main fire, they will not prevent additional fires from starting due to ember transport. The potential for ember transport in New Zealand has not yet been well studied. Torching trees (e.g. Kānuka) can generate embers and there are observations that some non-tree species also produce embers under the right conditions, such as bracken fern (*Pteridium* sp.), and gorse.

Influence of interacting factors/stressors on wildfire

Globally forest mortality is not only caused by fire but also by severe weather conditions (e.g., storm, hurricane, drought, etc.), and insects and disease (van Lierop et al., 2015). These factors result in direct mortality and widespread vegetation stress (Conklin & Armstrong, 2001; Piirto et al., 1998). This mortality and stress can significantly alter the fuel hazard and resulting potential fire behaviour. Forests impacted by stressors or natural disturbances are assumed to be more flammable than a healthy forest, due to a reduction in foliar moisture content, and an increase in the amount of dead material present, therefore posing a greater fire hazard compared to healthy forests. The change in hazard and fire potential differs based on the amount of disturbance and or stress (Figure 15, Table 2). The magnitude of this stress and subsequent wildfire hazard can be described in four phases: 1) stressed canopy, 2) partial or full loss of canopy foliage, 3) tree mortality, and 4) stand mortality (Figure 15, Table 2, Table 3). These phases are not necessarily discrete but could be intermixed at the stand or landscape level depending on the disturbance.

During the stressed canopy phase, there is an increase in ignition susceptibility and spread. In dense stands this could also lead to an increase in the potential for crown fires. Once there is partial or full loss of the canopy, surface fuel load and fire intensity will increase and there is an increased likelihood for torching of trees. Tree mortality will lead to an increased potential for deep seated ground fires during drought conditions. Full stand mortality may decrease ignition and spread potential in cases where there are no surface fuels, but this decrease will only last until early seral forests have re-established (Table 3).

Various types of disturbance can interact with each other, causing feedback cycles where a disturbed forest is more susceptible to additional disturbance. Any one or a combination, of stressors above can initiate forest dieback, and initial mortality from one stressor may lead to further mortality from another (Ogden, 1988).   For example, insects and disease outbreaks lead to fuel accumulation that later supports more intense fires, which also leads to an increase in pest/disease vulnerability (Koch, 1996; Parker et al., 2006). Whereas fires increase the propensity of trees to be attacked by pests and diseases: bark beetles are typically considered as the most important damaging insects after fires because they commonly attack trees that were weakened but not killed by fire (Conklin & Armstrong, 2001; Fowler & Sieg, 2004; Thies et al., 2001).

Multiple abiotic and biotic factors which can negatively impact forest health (Table 2, Appendix 2) are predicted to increase in New Zealand (Watt et al., 2019). Forests in New Zealand can be impacted by everything from localized/point disturbances (at the individual tree scale) to landscape wide destructive events (at the stand level). Strong winds are the most common widespread disturbance in New Zealand forests, with the greatest vulnerability in stands with tall trees, saturated soils, or sites that have been recently disturbed (Wyse et al., 2018). Wind-damage can initiate forest dieback in beech forests as the resultant abundant woody debris harbours the larvae of pinhole borer (*Platypus* spp.); the adults of which attack living trees and act as a vector for the fungal pathogen *Sporothrix* sp., leading to tree death when the beetles are present in sufficient numbers (Hosking & Hutcheson, 1986; Ogden, 1988). As with wind-throw, the effects of both snow-break and drought can act synergistically with insect and pathogen attack, a phenomenon particularly noted in beech forests (Hosking & Hutcheson, 1986; Skipworth, 1981; Wardle & Allen, 1983).

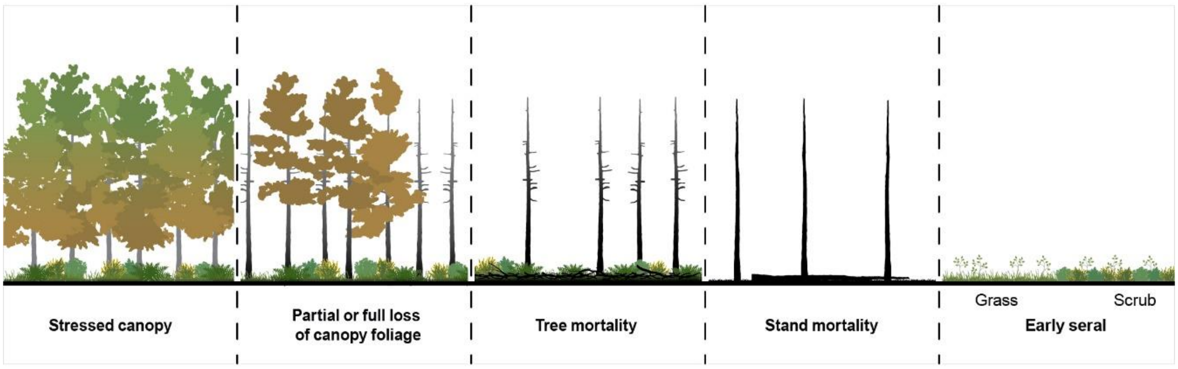

Figure 15. General classes of forest stress (See Table 2 & 3 for additional details) that influences wildfire hazard and risk. Following stand mortality there will be a transition early seral. Graphic Design Credit: Dale Corbett, Scion.

Table 2. General classes of disturbance and subsequent types of forest stress that can cause landscape level disturbance (Table 3 that influences wildfire hazard and risk.

Disturbance Class	**Type**	1) Stressed Canopy	2) Partial or full loss of canopy foliage	3) Tree mortality	4) Stand mortality
Weather events (due to extreme conditions, or changes in the climate)	Strong winds		x	x	x
	Intense rainfall resulting in flooding				x
	Snow damage		x	x	
	Late spring frosts/frost curing	x	x	x	
	Multiple days of hot/dry windy weather	x	x		
	Prolonged drought	x	x	x	
	Wildfire	x	x	x	x
	Lightning strikes	x	x	x	
Pests and Disease	Pathogens (fungi, bacteria, and viruses)		x	x	
	Insects		x	x	
	Herbivores (including pig, deer, possum, rabbits, and hares)	x	x		
Geologic events	Earthquakes			x	x
	Volcanoes				x
	Landslides (due to earthquakes or heavy rainfall)				x

Table 3. Phase of forest stress linked to disturbance type, impacts to the forest and subsequent wildfire hazard and risk.

Phase of Forest Stress	Disturbance	Impact to Forest Structure and Composition	Fuel Hazard	Potential Fire Behaviour
1) Stressed Canopy	Wildfire (low/moderate intensity surface fire), frost/snow curing, several days of warm dry windy weather, drought, herbivory.	*Foliage reacts to heat and water stress by either closing the stomata, wilting, curling, or curing. *The length of time leaves cure and persist in the canopy depends on the tree species, location, timing of the year and the weather conditions.	*Increase in flammability and fire hazard. *Reduced foliar moisture content reduces the amount of energy required for combustion, making the canopy easier to ignite in comparison to a healthy forest. *Increase in total canopy fuel available for combustion, potentially leading to extreme fire behaviour.	*Increased likelihood of ignition and spread into the canopy under a wider range of weather conditions. *In high density stands, increased likelihood of running/continuous crown fire.
2) Partial or full loss of canopy foliage	Wildfire (low/moderate intensity surface fire), frost/snow curing, several days of warm dry windy weather, drought, insects, pathogens, herbivory	*Foliage is desiccated and falling from trees, increasing surface litter. *Gaps in the canopy or complete canopy loss alter the microclimate exposing the understory vegetation and forest litter to the weather elements, decreasing moisture. *Light tolerant and pioneering species may begin colonization in gaps changing species composition.	*Increased surface fuel - fine fuels (leaves) and medium fuels from branches. Decreased canopy fuel. *Ignition susceptibility of fine fuels increases because of drying and increased fuel load.	*Increased surface fire intensity. *Torching of trees where dry foliage remains (partial canopy loss).

Phase of Forest Stress	Disturbance	Impact to Forest Structure and Composition	Fuel Hazard	Potential Fire Behaviour
3) Tree mortality	Strong wind or snow events, intense wildfire, drought, Insects, Pathogens, Earthquake	*Large accumulations of coarse woody material (branches and stems) on the forest floor. *Dead standing tree stems. *Light tolerant and pioneering species begin to colonize shifting the stand to early seral in areas of high mortality.	*Increased ease of ignition, greater potential for surface fire spread and higher fire intensity. *The length of this increased flammability will depend on the amount and size of surface fuels, the rate of decomposition, fuel moisture and other vegetation present.	*Large surface fuels may have higher moisture contents, so that fire intensities and flame lengths are less than disturbance classes 1 and 2. *Under prolonged drought all fine and coarse woody fuels would be available for combustion and contribute to high intensity surface and deep-seated ground fires. *A fast-moving grass or scrub fire amongst downed or dead standing trees is likely following establishment of early seral species.
4) Stand mortality	Volcanic event, landslide (from heavy rainfall or earthquakes), flooding, extreme wildfire, severe earthquake/ liquefaction.	*Surface organics (soil, litter, vegetation) are largely absent with bare/scorched ground. May be coarse woody stems on the ground if not completely consumed/moved). *Light tolerant pioneering species eventually establishing; establishment may take longer if site nutrients and soil have been depleted.	Varies depending on the amount of coarse woody fuels and surface fuels remain. In general, fire hazard would be low until early seral species have established.	In the absence of fuel, fire ignition and subsequent spread will be limited until early seral species establish.

Forest Recovery

It is important to recognize that ecological recovery is complex and influenced by micro and macro scale site context (i.e. topography, aspect, moisture), site history (i.e. previous disturbance), and species at the recovery site as well as species in the surrounding landscape (e.g. for seed source, seed predation by mammals). In addition, the likelihood of disturbance in the future, including but not limited to disturbance from fire, is likely to be altered and therefore the recovery processes may be different than what we have seen in the past (Wyse et al., 2018). Regardless, knowledge from past recoveries can inform how future forests may recover from disturbance. In the context of this report, we are defining recovery primarily from an ecological perspective, i.e. when a functioning forest ecosystem returns following disturbance. However, it is important to recognise that recovery is also part of the 4 Rs (Civil Defence integrated approach to emergency management - Reduction, Readiness, Response, and Recovery) where recovery is focused on societal recovery. The economic complexity of fire as a disturbance is briefly discussed.

Historically, large disturbances were infrequent in New Zealand although natural disturbance processes still resulted in dead and dying trees dotted across the landscape (Jane and Green 1983; Wyse et al. 2018). New Zealand forests did not evolve with frequent fire because fire as a disturbance in New Zealand is largely an anthropogenic disturbance. Therefore, most native New Zealand species are not adapted to frequent fire, with some exceptions in tea trees (e.g. mānuka) and *Pomaderris* spp. (Battersby et al., 2017; Kitzberger et al., 2016). Kitzberger et al. (2016) demonstrated that an increase in fire has changed the species composition on the New Zealand landscape, by increasing species with fire-adapted traits and decreasing species with a low tolerance to fire. Fire intensity alone does not determine the impacts a wildfire has on tree survivability or mortality. Tree injury and mortality can arise from various levels of damage to the crown (foliage), and vascular or root tissues. The following factors and the interactions of these factors are important for wildfire resistance (tree survival) or sensitivity (damage and mortality):

Fire behaviour:

- The level of fire intensity (Fernandes et al, 2008), where higher fire intensities will tend to lead to more damage and death.
- The type of the fire (ground, surface and crown fire) where a crown fire will have higher intensities than a surface fire. A ground fire may cause pockets of mortality due to root damage where there is a long duration of heat from smouldering, whereas surface and crown fires will spread across the stand.
- Residence time of the fire type burning where the longer the residence time, the more likely mortality will occur. Heavy fuels or duff layers will increase the residence time of the fire and therefore the likelihood of damage (FFMG, 2007).
- Individual tree response to the fire as a measure of the extent of crown scorch, crown consumption, and the height and percentage bole charring (Fernandes et al, 2008) where increases of any of these variables will increase the likelihood of damage and mortality.

Tree traits:

- Bark thickness and the variability in the bark thickness along the tree will influence if the tree cambium is killed (Mead, 2013; Fernandes et al, 2008). The structure, composition and density of bark will provide various insulating capacity.
- The moisture content of the inner bark where the drier the bark, the more likely mortality will occur. This moisture content various seasonally and is often lower in summer which increases likelihood of damage (FFMG, 2007).
- Forest floor composition where the more the build-up of fuels (fine, medium and coarse) and the lower the moisture content of the fuel will increase steam girdling and root damage (Fernandes et al, 2008; FFMG, 2007).
- Tree size where a smaller diameter and/or shorter tree will have a greater likelihood of death following the fire (Fernandes et al, 2008).

- The base height of the crown will determine the distance to the flame (if a surface fire or ground fire) where the taller the crown base height, the less likely there will be mortality (Fernandes et al, 2008).
- The structural arrangement of canopy foliage affects heat transfer by convection (Fernandes et al, 2008).
- The individual plant's ability to resprout following a fire, which will decrease the likelihood of mortality.
- Bud tolerance to heating (inferred from bud width), bud shielding from heat provided by needles, and time-temperature thresholds for needle and bud necrosis (Fernandes et al, 2008).

Forest recovery following fire is dependent on both survival during the fire and regeneration after – either from seeds and/or from resprouting (vegetative regeneration following a disturbance from a source of protected buds - (Clarke et al. 2013)). Seed dispersal limitation has been documented globally and nationally as an important factor in forest recovery (e.g. Kitzberger et al., 2016; Steel et al., 2015), where the larger the fire, the less likely seed regeneration will occur in the interior of the fire. In addition to seed regeneration, the soil community including ectomycorrhizal species can be significantly altered following fires depending on fire intensity (e.g. Pulido-Chavez et al. 2021). Therefore, the fire size and size of mortality patches within the fire are critical aspects of recovery. When discussing recovery following fire, it is critical to put the forest response in the context of the fire intensity. There are a limited number of studies in New Zealand specific ecosystems, and even fewer of these studies successfully tie fire behaviour (intensity, rate of spread) to the outcomes. At a very high level, the larger the burned patch, the longer the recovery may take.

Native Forest Recovery

Most forest fire recovery case studies have focused on beech forests (*Fuscopora* spp.). Nothofagus and podocarp species in mesic-dry forests that are poorly adapted to fire due to thin bark, shallow roots, and susceptibility to rot following disturbance (Kitzberger et al., 2016). This makes them vulnerable to mortality from all types of fire, including lower intensity ground and surface fires. Following a fire that causes large-scale mortality, beech recovery can take decades because of heavy, short seed dispersal distance (tens of meters), short-lived seed viability, and strong ectomycorrhizal requirements (Wardle, 1970). Where historic fires have occurred some forest stands (beech and podocarp dominated) have shifted to herbaceous, and shrub dominated systems. In native beech and podocarp forests, regenerating stands are often dominated by bracken fern, which is highly flammable and continues to persist following small frequent fires (McWethy et al., 2010; Wilmshurst & McGlone, 1996). In addition to bracken fern, these stands include other early seral species in the Poaceae and Asteraceae families (McWethy et al., 2010; Whitlock et al., 2015; Wilmshurst & McGlone, 1996), which are easier to ignite and cause rapid rates of spread. Small trees and scrub follow grass and forb succession with flammable mānuka and kānuka being most frequent (McWethy et al., 2010; Whitlock et al., 2015; Wilmshurst & McGlone, 1996). Non-native species also invade into the scrublands following fire, including heath (*Erica* spp.), hakea (*Hakea* spp.) and gorse which is a highly flammable species (Kitzberger et al., 2016; Wyse et al. 2016). Native forests may not establish for 125-200+ years, depending on moisture, seed availability, (Whitlock et al., 2015; Wilmshurst & McGlone, 1996) and mycorrhizal community. In general, forest development will be quicker at wetter sites (Wilmshurst & McGlone, 1996) and in smaller burn areas or at the edge of the burn perimeter where there is a nearby seed source (Whitlock et al., 2015). With active management and exclusion of fire these scrublands can develop into forests quicker (McWethy et al., 2014).

Resprouting is an important strategy for recovery following fire (Teixeira et al., 2020), especially in areas where a disturbance is very large and there is no local seed. While some species can resprout following disturbance (e.g. taraire [*Beilschmiedia taraire* Bentham & Hooke], broadleaf [*Griselinia littoralis* (Raoul) Raoul], kamahi [*Weinmannia racemosa* L.f.]), very little is known about how re-sprouting traits correlate to post-fire response (Kitzberger et al., 2016). Teixeira et al. (2020) provide the first quantitative assessment of native New Zealand species that are capable of resprouting, however only a handful of the resprouting traits were evaluated following a fire and with those species the ability and persistence of resprouting was not correlated with fire intensity. An important finding of a review conducted by Teixeira et al. (2020) is that while many smaller trees and shrubs are adapted to resprouting, dominant native canopy species do not have much resprouting capability. The one exception being kauri (*Agathis australis* (D.Don) Lindl) which is capable of resprouting, although is also noted to be sensitive to fire (Teixeira et al., 2020).

Plantation Forest Recovery

In the future as fire increases across the landscape, plantation managers may need to decide if they are going to re-plant or wait for natural succession. Currently natural succession is unlikely within plantations damaged by fire because managers will replant and manage the plantation rather than wait for natural succession to occur. This limits data within New Zealand regarding what succession and recovery within plantations looks like. However, inferences can be made from international literature. Radiata pine, the dominant plantation species in New Zealand and a fire adapted species, is known as a post-fire invader, especially in areas outside of its natural habitat (Ripa et al., 2023). The species does not have the ability to resprout after a fire; therefore, recovery relies solely on post-fire seed germination from the serotinous cones which is influenced by fire intensity and smoke (Reyes et al., 2015). Reyes et al. (2015) found that germination success decreased as fire intensity increased, with high germination only occurring in areas experiencing low to no fire. Whereas Ripa et al. (2023) found that in a laboratory setting recurrent fires fostered germination and early growth of radiata pine, suggesting the species could invade following fire. Based on limited data, it is unclear how radiata pine plantations would recover from fire in the absence of management interventions in New Zealand. Some natural regeneration is likely, but it is unclear if the extent of the regeneration would be suitable for a plantation and if radiata pine would become dominant or if over time native forest species would become dominant.

Wilding Pine Recovery

New Zealand literature is limited on wilding pine recovery following fire. While wilding species such as lodgepole pine [*Pinus contorta* Dougl. ex. Loud] and Douglas-fir evolved in frequent fire regimes and possess a variety of traits to persist across varying fire frequency and severity, there are undocumented observations which suggest that wildfire can both cause overstory mortality and reduce future invasion of wildings. The Mount Cook Station Fire of 2008 burned 15-20 m tall wilding tree species (90% Corsican pine [*Pinus nigra* Arn.] and 10% European larch [*Larix decidua* Larch]) (Clifford & Pearce, 2009). This wildfire had high burn intensities where the wildfire moved into the deep organic soil layers (high soil temperatures), resulting in overstory mortality. Following the wildfire, observations have shown limited reinvasion of these species into the area. There have been two large wildfires near Lake Pukaki that burned at medium to high intensity through mature lodgepole pine stands. Based on observations from a 2020 wildfire, regeneration of wildings is low in areas of standing dead trees potentially due to competition with a high cover of grasses and forbs. However, in areas that were cleared of standing dead trees, regeneration is active among windrows. A case study investigating the mortality of seedlings and saplings following a 2023 wildfire shows that in young wilding stands, mortality of wilding seedlings and saplings was greatest where the wildfire was carried more easily on slopes and in areas with greater fuel (higher grass cover) (Gross et al., 2024c). These results are complimentary to work done in the United States where experimental burns showed that lodgepole pine mortality is most likely to occur where there is continuous dry vegetation, small trees, and a hot flaming front (Frenzel, 2012). Considering some of the observational evidence that wildfire may cause wilding mortality, there have been discussions about the efficacy of fire as a tool for wilding control. While wildfire is likely an effective tool, it is important to understand the context and wildfire intensity needed to efficiently use wildfire to manage wilding stands.

Feedback on future fire

Multiple studies have presented the concept that anthropogenic fire is changing the fire regime within New Zealand (Kitzberger et al., 2016; Whitlock et al., 2015), because in many instances fire as a disturbance creates a feedback where future wildfires will ignite and spread easier. For example, beech forests often transition to mānuka scrubland following fire (Wardle, 1970). Beech forests provide a cool, moist microclimate below the canopy which reduces fire activity. In contrast, an early seral bracken fern-mānuka-kānuka grass scrub easily dries out allowing fire to travel in the understory and transfer flames to the shorter flammable scrub species (Kitzberger et al., 2016), the fire hazard of the stand remains high until the native tree species are tall enough to produce a cooler, moisture microclimate that shades out early seral flammable species (Whitlock et al., 2015).

Indirect Fire Impacts

In addition to direct forest mortality, forest fires have short and long term indirect ecological and economic impacts. These short-term impacts include (but are not limited to) human and property loss, physical cost of the fire, air pollution from fire and subsequent health effects, water and soil contamination, habitat loss, timber loss, and the release of carbon dioxide. Long term impacts include (but are not limited to) the need for multiple hazard planning, erosion, and due to the changing environmental conditions, a long-term reduction in timber output, recreational values, the loss of carbon, and shifts in flora and fauna communities – including an increase in invasive species. While there is limited documentation in a New Zealand specific context, palaeoecological records have demonstrated that repeated high severity fire in New Zealand leads to changes in not only the vegetation, but also slope stability (Cumberland, 1944; McSaveney & Whitehouse, 1989), water quality (McWethy et al., 2010), and nutrient depletion (Kitzberger et al., 2016; McIntosh et al., 2005). New Zealand's complex topographic terrain with steep slopes and neighbouring waterbodies suggests that erosion, soil quality and water quality outcomes following wildfire should be closely tracked. There is a further feedback where early seral vegetation causes further nutrient depletion reducing organic matter, whereas later successional classes support wetter micro-sites which hold onto more carbon (McIntosh et al., 2005).

Economic recovery

In addition to forest recovery, there is the economic aspect of what it takes to recover a forest that is being actively managed. Teixeira (2021) looked at factors influencing post-fire native species planting success, and her results align with patterns seen globally in that planting success is influenced by species, seedling height, existing vegetation, and weed control. In addition to these factors, site conditions following the planting are extremely important. For example, if you have periods of drought following planting then those seedlings may not be as likely to survive; alternatively, if you have heavy rains on steep slopes the seedlings could be washed away. Another critical factor to consider is the site preparation requirements. In many situations, especially in plantation management, standing dead timber needs to be removed or felled to allow a new seedling cohort to be planted. These costs can be substantial, especially in situations where the timber cannot be salvaged due to it being badly scorched, mills are not capable of processing wood in time, or fungi have already moved in. It is our understanding that following the 2017 Port Hills wildfire most of the wood could only be processed as bark mulch.

Blanc and Noy (2024) demonstrate potential economic impacts of recovery activities based on the level of forest mortality. They identify fire remediation and clearing costs necessary prior to planting, including costs of fencing, erosion, windrowing, and felling (shearing) (Blanc & Noy, 2024). While actual costs vary, the paper highlights the downstream costs associated with reestablishing forests following wildfire. The economic impact of disturbance is important to understand to prioritise limited resources. Future work should evaluate and track outcomes and opportunities following wildfire in plantations.

Opportunities for mitigation and management of wildfire risk

Wildfire risk and hazard can be managed at both the stand and the landscape scale by reducing the potential for fires to ignite, and by treating fuels in advance to reduce fire behaviour and damage if they do ignite. There are various management strategies and recommendations that have been developed or implemented by national and local government agencies and bodies, commercial landowners, and private landowners. Some of the most valuable New Zealand specific mitigation guidance includes the *Forest Fire Risk Management Guidelines* (NZFOA., 2018) which provides information on steps to avoid or mitigate fire impacts, the update to the fire risk management guidelines for small forest owners (NZFOA/FFA., 2020) and the *Wildfire Risk Management Plan guidelines* (2022) which builds on the 2018 guidelines by adding specific site actions that increase ease of suppression. Large corporate forest owners invest significant resources into fire risk management (NZFOA/FFA, 2022). For example, forest owners maintain trained firefighting personnel and equipment, install and maintain firebreaks and firefighting ponds, and in some cases have manned fire lookout towers, and undertake aerial patrols. Fire and Emergency New Zealand (FENZ), who have authority over wildfire response at a national level, have also developed plans for reduction, readiness, and response which apply to forest management which focus on developing guidance around when to limit activities, how to communicate current conditions and activity limits, and how to map regions for advanced planning.

Wildfire in New Zealand is managed based on the Civil Defence integrated approach to emergency management using the 4 R's: Reduction, Readiness, Response, and Recovery. Advanced preparation and reduction have been shown to yield considerable savings over suppression of a wildfire (response) (Prestemon et al., 2010; Wu et al., 2009). When compared to unavoidable natural disasters in New Zealand such as earthquakes, volcanic eruptions, and to a degree flooding, wildfire risk reduction is especially valuable since wildfire in New Zealand is primarily human caused, and therefore there is an opportunity to prevent the hazard. Planning, fuels management, and education are key reduction and readiness practices to minimize wildfire hazard and risk in New Zealand.

Planning

Planning plays a crucial role in minimizing the risk and impact of forest fires by avoiding instances that may cause wildfires to occur in the first place and ensuring that response is fast and effective in suppressing them if they do occur. The Landscape Fire Governance Framework (https://www.wildfire2023.pt/conference/framework) is starting to be considered within New Zealand, as it identifies the value of integrated landscape management and provides a governance model to improve coordination.

Risk analyses can identify and assess threats using a variety of tools such as expert knowledge, fire growth and behaviour models, fire suppression effectiveness models, and economics-driven wildfire decision tools. In New Zealand, fire behaviour and spread modelling software (e.g. Prometheus, https://firegrowthmodel.ca/pages/wise_overview_e.html) has been useful for landowners to determine which areas may most impacted by fire, and how fuel treatments may reduce the impact (Christensen, 2022). The New Zealand Fire Behaviour Toolkit calculator (https://www.ruralfireresearch.co.nz/resources/tools/fire-behaviour-toolkit) allows users to calculate anticipated fire behaviour and determine fuel (fire) break effectiveness, but does not offer management solutions.

Once high hazard/risk areas have been identified, risk mitigation plans can be developed (e.g. development of policies regarding fire-safe work practices, emergency response plans, fuel and asset map planning, fire response agreements, and operational plans that account for potential fire). This advanced planning can reduce fire risk through fast and effective response. It is important to note that co-development of mitigation strategies is often more effective than individual land managers working alone. Brzuszek et al. (2010) found that co-developed deliberate fire mitigations, such as fuel breaks and buffers, reduced fire behaviour resulting in less impact to communities compared to wildfires that occurred where identification and preparation of breaks were less deliberate.

Most wildfires in plantation forests do not originate from forestry activities, but rather come from external sources (Cameron et al., 2007a), therefore the effectiveness of permanent and variable practices that forestry companies use is dependent on ignition sources. Permanent forestry practices that reduce wildfire ignitions include maintaining and modifying equipment to reduce spark and hot ember creation, and controls on how equipment is used (such as not parking or fuelling in at-risk areas) (NZFOA., 2018). Variable work practices are specific mitigations that are introduced as the predicted fire danger increases, with the intent of avoiding ignitions or catching ignitions before they have an opportunity to grow out of control. These mitigations include gradually increasing restrictions on different types of work, as well as increases in precautionary measures such as fire patrols. As fire danger increases forestry companies will introduce smoke-watch periods following work, station lookouts at key locations, and increase fire patrols. They will also implement internal restrictions on specific activities such as mowing, harvesting and silviculture operations, and hot-works, and may limit access for contractors and/or the public (Pearce et al., 2016).

Fuel Management

If a wildfire does occur, fuel management strategies (fuel breaks and fuel reduction treatments) can have a significant effect on the fire behaviour and subsequent risk. Fuel management seeks to change fuel load, structure, and continuity to reduce fire behaviour and limit fire spread (Agee & Skinner, 2005). Fuel management can be performed at the landscape level to reduce overall impact of large fires and potentially reduce spread, or at a local level to protect specific assets (e.g. individual structure, city, forestry holding). The combination of fuel thinning treatments and fuel breaks has gained international recognition as part of the Canadian FireSmart and United States Firewise programs (FireSmart Canada 2024; Firewise 2024). While FireSmart and Firewise primarily focus on fire treatments to protect structures and communities, the underlying fire behaviour and control principles are applicable in any situation where the intent is to limit fire spread.

In addition to fuel breaks, there are a range of management options that can be used within a forest to reduce fire behaviour. Fuel reduction treatments can involve manual or mechanical thinning and pruning of fuels (both ladder and understory fuels), grazing, weed control, mowing, and/or controlled burning (also called prescribed fire). Grazing and weed control can reduce fuel height and continuity, reducing fire spread and flame height potential. Grazing can also be used to promote regeneration of early successional natives, which can be effective in reducing rank grass or other target species to reduce fuel loading. Forest thinning and pruning is often used to improve wood quality but can also benefit fire behaviour by reducing the continuity of canopy fuels, thus reducing the potential for a continuous crown fire. It is important to note that, depending on the silvicultural prescription, these activities can also increase woody material on the surface for a period which increases surface fuel hazard until they decompose sufficiently. Low intensity prescribed fire has been used as an effective tool both overseas and historically in New Zealand for removing woody fuels, and to thin standing understory fuels (Fernandes, 2015; Hislop et al., 2020; Waldrop et al., 2016) (Figure 16). However, softwood plantations in New Zealand are considered more sensitive to fire. Radiata pine is considered a fire sensitive species because it will die if the whole crown is scorched which can occur when the fire intensity is less than 2500kW/m (FFMG, 2007 & Mead 2013). However, it is possible to carry out fuel-reduction burns under older trees if the fires are low intensity (200–300 kW per m) and the duff does not ignite (Mead 2013). For this reason, fire in New Zealand is primarily used to clear land for farming or planting, and/or to remove logging debris, rather than for under-burning as is sometimes done overseas.

Figure 16. A low intensity prescribed fire designed to remove surface fuels (tree regeneration, pine needles, pinecones) and reduce future fire hazard to protect endangered species habitat. Photo credit: Tara Strand.

Education

Historically in New Zealand, planned burns are the main cause of wildfires. Therefore, improved education and burn permit enforcement could reduce these instances, as many of these escaped fires are likely preventable. In Florida, wildfire education programs were shown to reduce the number of accidental fires with a cost savings of 10-99 times the cost of the education compared with the cost of fighting fires (Prestemon et al., 2010).

It is important to not only educate forestry owners, but also the adjacent landowners who surround the forests and the public who recreate within the forests. In New Zealand, there are varied perceptions from communities about wildfire awareness, risk, and mitigation actions, and thus varied views around responsibility for mitigations (Langer et al., 2023). While individual education is important (Grant et al., 2017; Hart & Langer, 2014), local and national education is critical as well. Current Scion research suggests that planners, transport and Geotech engineers, architects and landscape designers are generally not aware of wildfire risk, do not include mitigations for wildfire in their planning, and struggle to determine suitable mitigations if presented with the issue.

Additionally, education and training are important for fire response crews to effectively put out fires quickly. Due to the low frequency of wildfires in New Zealand, these crews do not receive consistent real-world training and experience with fire but rely on exercises or academic courses. Internationally it is understood that effective wildfire suppression must include real-world fire experience, with training including burn-offs and frequent wildfire response to maintain skills and develop knowledge. Currently many landowners, including forestry managers, train their staff for wildfire response inside and around their land because they have the local knowledge and understanding surrounding forestry hazards, thus reducing the risk of fire.

Knowledge gaps

A substantial amount of the considerable knowledge on wildfire available in New Zealand has been translated from overseas expertise and has not always been validated for New Zealand conditions (Opperman & Pearce, 2005). While much of this knowledge is applicable and appropriately applied, there are still significant knowledge gaps in the New Zealand specific fuels and landscape context.

Additionally, as the landscape changes from multiple disturbances, and succession processes adapt, wildfire risk and hazard will also change. The best way to understand the wildfire risk and hazard of afforestation is to monitor outcomes of afforestation and evaluate how agents of change influence forest stands and forests across the landscape.

Based on this review, we have identified eight key knowledge gaps where research would improve our understanding of wildfire in New Zealand.

1. **Validate and further develop new fuels models.** Validate and refine current fuel models for the New Zealand environment and develop new fuel models, specifically for (but not limited to): 1) broom scrub – as distinct from gorse/mānuka scrub, 2) indigenous forest types by species and seral class – which are currently only separated based on available fuel load, 3) other plantation species (e.g. not radiata pine but eucalypts or redwood), 4) wilding pines – by seral class (age/density) and species.

2. **Increase the understanding of extreme fire behaviour for different fuel types.** Fire behaviour is often based on data collected for fuel types during low to moderate intensity fires and does not capture extreme conditions. However, it is important to understand how each fuel type burns under the full range of conditions – especially extreme conditions to properly inform suppression activities and community and firefighter safety.

3. **Identify the physical and biological factors contributing to ember transport for New Zealand species**, including the identification of the size, number flux, distances, and propensity to ignite spot fires. Currently fire simulations do not include medium to long-range spotting/ember transport as a function of the main fire but treat successful ember ignition and propagation as new fires. There is a need to understand and simulate how ignition and propagation of spot fires interact and affect resulting fire behaviour.

4. **Quantify the importance of live fuel moisture content on fire behaviour.** In New Zealand, no studies have been carried out to document the changes in moisture content of live fuels on the ease of ignition and propagation of fires. This is important given that live foliage is the main fuel component involved in high intensity crown fires.

5. **Influence of interacting stressors on forest hazard and fire risk and subsequent forest resilience.** There is value to researching how the interaction of multiple stressors change wildfire risk and hazard. At present, most of our understanding is based on assumptions/ hypothesis developed from international cases and basic physical and biological processes.

6. **Improve fire location data to improve the understanding of what drives wildfires in New Zealand.** The Scion research team has developed a prototype to store wildfire occurrence data in an accessible consistent format where the data can be explored to answer questions about seasonality, weather and fire danger conditions, and fuels to increase knowledge around wildfire in New Zealand. This foundational data is primarily point data and does not represent the full extent of the fire (polygon data) or often the correct location of the fire (due to reporting against address points). To improve our understanding of what drives fire, we need better basic fire location and perimeter data, ideally associated with severity and improved fuel type and condition information.

7. **How do forests in New Zealand recover following disturbance and what land management interventions may be needed.** In most cases, past research has not linked fire behaviour (intensity, rate of spread) to forest recovery. This is essential because the complexity of the landscape and disturbances process will lead to different long-term successional trajectories, and these trajectories may change over time as the landscape changes. Research should evaluate and track outcomes and opportunities following fire in both unmanaged and managed forests. For example, it is unclear how radiata pine plantations would grow after a fire in the absence of management intervention. If the scale of disturbance is beyond what is economically viable, then prioritization will be needed for limited resources.

8. **Evaluate how the scale of management / mitigation strategies changes wildfire hazard and risk.** Landscape scale wildfire risk and hazard is a complex topic, with most people thinking about mitigation strategies at the stand level, however these can (and should) be evaluated at multiple scales. This includes strategies associated with planning, fuel management, and education. Specifically, the efficacy of fuel breaks has been identified as something that should be evaluated and potentially updated based on New Zealand fuels and weather.

Conclusion

Wildfire risks and hazards for afforested landscapes are dependent on pre-afforestation fuel type, target forest system, and the landscape context in which the forest was planted (i.e., dry catchment or southerly facing moist hill), surrounding land use and human activity within and around the new forest. The wildfire risk potential will change with time as these factors change.

The potential hazard for a fire to start and spread is higher in initial stages of afforestation (early and mid-seral classes where there is a high grass or scrub cover), and lower in later stages of afforestation (where there is a decline in grasses, flammable scrub, and an increase in moisture). Noting, however that under extreme wildfire risk conditions a wildfire can start anywhere and in any fuel type. As the forest ages, there is an increase in biomass / fuel and a potential increase in horizontal and vertical connectivity, which will allow the fire to travel quickly. This translates to a higher fire severity potential in older forests, compared to younger forests – if an ignition is successful.

Management activities can reduce the potential for spread and severity. Thinning and pruning of forests can reduce the fuel load and potential for the fire to reach the canopy, thus reducing severity. These activities also limit spread. Further management of surface fuels and using both natural and anthropogenic fuel breaks further reduces the likelihood of a fire igniting and spreading both within the forest, but also from outside of the forest. Fuel reduction practices, such as grazing, controlled burning of the surface fuels and mulching also reduce fire ignition and intensity potential.

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Glossary

4 Rs: The New Zealand integrated approach to Civil Defence & Emergency Management can be described by the four areas of activity, known as the '4 Rs' – Reduction, Readiness, Response and Recovery (National Emergency Management Agency, 2020).

AFL (Available Fuel Load): refers to the amount of fuel biomass that would be consumed under specific burning conditions and is mainly influenced by moisture content, size of the fuel particles, presence of dead fine material and/or chemical compounds in the foliage.

BUI (Build-up index): A numerical rating of the total amount of fuel available for combustion which provides information on potential fire behaviour after initial spread

Carbon Forest: A forest managed primarily for carbon sequestration, capturing and storing carbon dioxide with the ability to earn a reward for carbon sequestration.

Closed canopy forest: refers to a forest that has tree crown cover of more than 80% of the land area

Crown fire: a fire that has moved from the surface into the forest canopy. (see passive crown fire, active crown fire, and independent crown fire)

Crown fuel (also known as aerial fuels): fuels found in the tree canopy.

Continuous crown fire: A crown fire in which both the surface fire and the crown fire are active. Surface fire intensity is sufficient to ignite tree crowns, and fire spread and intensity in the tree crowns encourages surface fire spread and intensity (National Wildfire Coordinating Group, 2024). Also known as active crown fire.

Curing: Drying and browning of herbaceous vegetation due to drought, high temperatures, frost, mortality or senescence (AFAC, 2012; Sjöström & Granström 2023).

Ember: a small, hot, glowing particle composed of carbon-based material such as wood or coal. Embers may remain during, after, or even precede a fire, retaining high temperatures and posing a risk for spreading fires.

Extreme fire behaviour: a level of fire behaviour that often precludes any fire suppression action. It usually involves one or more of the following characteristics: high rates of spread, high frontal fire intensities, crowning, prolific spotting, presence of large fire whirls, and a well-established convection column. Fires exhibiting such phenomena often behave in an erratic, sometimes dangerous manner (Merrill & Alexander, 1987).

Fire behaviour: the way a fuel ignites, flames develop, and fire spreads as determined by the interaction of fuels, weather and topography (NRFA, 1998).

Fire break: A natural or an artificial physical barrier against the spread of fire from or into any area of continuous flammable material defined by an absence of fuel. Often selected or constructed to protect a high value area from fire. See also fuel break, which is used synonymously in this paper.

Fire environment: the surrounding conditions, influences and modifying forces of topography, fuel, and fire weather that determine fire behaviour (Countryman, 1972).

Fire hazard: 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).

Fire intensity: rate of heat release per unit length of the fire front (Byram, 1959), usually of the head fire where the fire is spreading the fastest.

Fire risk: the processes, occurrences or actions that increase the likelihood of fires occurring (AFAC, 2012).

Flame Height: Is the average maximum vertical extension of the flame front, from the base to the tip of the flame. See also flame dimensions and flame length

Flame Length: Is the actual length of the flames from the flame tip to the midpoint of the flame depth at the base of the flame. Flame length is an observable, measurable indicator of fireline intensity. Under no-wind conditions on flat ground, flame length equals flame height. Otherwise flame length will exceed flame height regardless of whether a fire is backing or heading.

Fuels: organic materials that ignite and burn in a wildfire, including live or dead combustible materials of trees, downed logs and sticks, grasses, scrub, and litter. [It is important to note that not all fuel is available for combustion; leaves could be too green and wet to ignite, and logs too large.]

> **Dead fuel**: organic materials that are no longer living and are susceptible to combustion. These fuels can be found attached to the plant or have fallen and are part of the surface fuels and can include branches, stems, leaves, twigs, and other plant matter
>
> **Live fuel: o**rganic materials composed of living vegetation, including grasses, scrub, trees, and other plants that contain moisture and contribute to fuel load in the landscape.

Fuel break: A natural or anthropogenic feature on the landscape defined by a change in fuel type (less flammable based on species or structure) designed to change fire behaviour and provide opportunities for suppression opportunities. (Also known as green fire break). See also fuel break, which is used synonymously in this paper.

Fuel layer: vertical and horizontal arrangement of fuel. (see: ground fuel, surface fuel, ladder fuel, crown fuel)

Fuel moisture content: a measure of the amount of water in a fuel (vegetation), expressed as a percentage of the oven dry weight of the fuel particle. Live fuels typically have higher moisture content compared to dead fuels. The ratio of dead to live fuel moisture content is important in assessing fire behaviour and potential to ignite and sustain a fire.

Ground fire: fire that consumes the organic material beneath the surface litter (i.e. ground fuels), such as a peat fire (AFAC, 2012; National Wildfire Coordinating Group, 2024).

Ground fuel: flammable material below the surface (e.g. tree roots, organic soil, duff).

Independent crown fire: occurs (rarely) where tree crown loading and flammability is sufficient to carry fire through the canopy without surface fire contribution under ambient weather and wind conditions (National Wildfire Coordinating Group, 2024).

Ladder fuel: fuels between the surface and tree crowns which can help spread fire into the canopy (e.g. shrubs, small trees, branches).

Mop-up: the actions taken to extinguish a wildland fire or part of a wildland fire that has been fully contained (Canadian Interagency Forest Fire Centre Inc (CIFFC), 2024).

Passive crown fire: (Intermittent or persistent torching): occurs where surface fire intensity is sufficient to ignite tree crowns, individually or in groups, but winds are not sufficient to support propagation from tree to tree (National Wildfire Coordinating Group, 2024). (also known as intermittent crown fire)

Rate of spread: the speed with which a fire moves in a horizontal direction across the landscape at a specified part of the fire perimeter (AFAC, 2012).

Readiness: developing operational systems and capabilities before a civil defence emergency happens; including self-help and response programmes for the general public, and specific programmes for emergency services, lifeline utilities and other agencies (National Emergency Management Agency, 2020).

Recovery: the coordinated efforts and processes to bring about the immediate, medium-term and long-term holistic regeneration of a community following a civil defence emergency (National Emergency Management Agency, 2020).

Reduction: identifying and analysing long-term risks to human life and property from hazards; taking steps to eliminate these risks if practicable, and, if not, reducing the magnitude of their impact and the likelihood of their occurring (National Emergency Management Agency, 2020).

Response: actions taken immediately before, during or directly after a civil defence emergency to save lives and protect property, and to help communities recover (National Emergency Management Agency, 2020).

Resprouting: vegetative regeneration following a disturbance from a source of protected buds and meristems (Clarke et al. 2013)

Seral Stage: Successional stages that a vegetation community undergoes from the beginning of establishment (early seral) to the climax/end community (old growth). The four stages identified include: early seral, mid seral, late seral, and old growth.

Severity (fire): degree to which a site has been altered or disrupted by fire; loosely, a product of fire intensity and residence time (National Wildfire Coordinating Group, 2024).

Seasonal severity: severity of fire weather and fire danger conditions, averaged over a month, fire season or year. Calculated from the daily FWI component of the Fire Weather Index system and intended to represent the workload required to control a wildfire based on the fire weather conditions.

Spot fire: fire ignited by firebrands (embers) that are carried outside the main fire perimeter by air currents, gravity, and/or fire whirls (Canadian Interagency Forest Fire Centre Inc (CIFFC), 2024).

Surface fire: fire that burns loose debris on the surface, which includes dead branches, leaves, needles and low vegetation (AFAC, 2012).

Surface fuel: fuels found on the forest floor (e.g. leaves, needles, cones, twigs, grass).

Torching: the ignition of a single tree or small group of trees from the bottom up (CIFFC).

Woody Debris: a combination of coarse fuels (>25 mm), medium fuels (6-25 mm), and fine fuels (<6 mm). Woody debris is sometimes referred to as slash when it is the result of plantation management activities.

Wildfire: any natural-caused or unplanned human-caused fire, including escaped prescribed fires, that is burning and consumes natural fuels (e.g. forest, brush, tundra, grass) (Canadian Interagency Forest Fire Centre Inc (CIFFC), 2024).

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Appendix 1 Relative Plant Flammability of 83 New Zealand Species

The concept of flammability is not a straightforward concept, and although it can be tested in the laboratory the flammability of a plant in the real world may vary due to environmental conditions and plant available fuel (CFA 2011). Field flammability will vary depending on:

- a plant's age, health, physical structure and chemical content,
- the daily and seasonal climatic variations,
- location of the plant in relation to other vegetation and flammable objects,
- the specific part of a plant – some parts of plants are also more flammable than others, and
- fuel (foliage) moisture content. Fuel moisture content is the most critical factor that determines plant flammability as it influences how a plant will ignite. Plants with high fuel moisture content will not burn until sufficient moisture has been removed from the leaves, whereas plants with low moisture content will ignite more rapidly and continue to burn (CFA 2011).

While published lists of species with high and low flammability exist, the information available can be misleading. Rigorous scientific assessment of the flammability of species is costly and time consuming making comprehensive lists difficult. For example, assessments based on experience can be subjective (e.g. influenced by opinion or infrequent observation), however fire managers possess a wide range of valuable field practicality. In comparison, laboratory experiments of leaf flammability do not indicate how a species will respond in the field because they have limited application in how the moisture content represents field level moisture and they ignore how the whole fuel complex ties to flammability. High flammability fuels have chemical and physical characteristics which greatly assist fire spread. These characteristics often include heavy fuel loads (McArthur 1967) with a high proportion of dead material (Sneeuwjagt and Peet 1985), as well as aerated and continuous arrangements (Cheney *et al*. 1992) which dry rapidly and provide ladder fuels or fuel bed bulk densities that promote combustion (Rothermel 1972). The individual fuel particles that comprise a fuel array may have one or more properties that enhance ignition and combustion such as a high surface area to volume ratio, low mineral content (Rothermel 1972), the presence of volatile oils or extractives, and low foliar moisture contents. An ideal flammability guide would combine elements of systematic laboratory experiments (capturing moisture content and whole plant level flammability) with fire management assessment.

This appendix includes exotic, indigenous endemic, and indigenous non-endemic shrubs, trees, graminoids, and ferns based on the best available information, however when using it the limitations above need to be considered. This collated list incorporates fire manager assessments of 47 native species (Fogarty 2002) with laboratory experiments of 60 native and exotic species at the leaf level (Wyse et al. 2016). Twenty-six of these species have both field and laboratory data associated with them. Confidence for flammability increases when these agree, 46%. Caution should be taken when these do not agree or where there is not the field level flammability has not been identified. When data was available for both the field scale and leave scale, 19% of the species burn at a higher flammability then identified in the lab, while 35% burn at a lower flammability. For example, laboratory work identified broom as having moderate/high flammability, however broom is known to be very difficult to ignite and only available for ignition when it is extremely well desiccated and piled. At the 2024 Port Hills fire, the fire effectively fizzled out when it encountered gorse. For this reason, we have manually adjusted broom to low

The scale used in this appendix ranges from low where a plan does not burn well and smoulders if it ignites to very high where the plant is easily ignitable burning hot.

Botanical name	**Maori/European name**	**Plant Form**	**Native/Exotic**	**Field Flammability (Fogarty 2002)**	**Lab Flammability (Wyse et al. 2016)**	**Comparison**
Coprosma robusta	Karamu	Tree	Indigenous Endemic	Low	Low	Agreement
Dysoxylum spectabile	Kohekohe	Tree	Indigenous Endemic	No data	Low	N/A
Fuchsia excorticata	Kotukutuku, fuchsia	Tree	Indigenous Endemic	Low	Low	Agreement
Geniostoma ligustrifolium	Hangehange	Shrub	Indigenous Endemic	Low	Low	Agreement
Myrsine australis	Mapou	Tree	Indigenous Endemic	No data	Low	N/A
Populus nigra	Lombardy Poplar	Tree	Exotic	No data	Low	N/A
Pseudopanax arboreum	Five finger	Tree	Indigenous Endemic	Low	Low	Agreement
Corynocarpus laevigatus	Karaka	Tree	Indigenous Endemic	Low	Low/Moderate	Field Lower
Griselinia littoralis	Papauma, Broadleaf	Tree	Indigenous Endemic	Low	Low/Moderate	Field Lower
Cytisus scoparius	Common broom or Scotch broom	Shrub	Exotic	Low*	Moderate/High	N/A
Carpodetus serratus	Putaputaweta, Marble leaf	Tree	Indigenous Endemic	Low	No data	N/A
Coprosma grandifolia	Raurekau, Kanono	Tree	Indigenous Endemic	Low	No data	N/A
Coprosma repens	Taupata	Tree	Indigenous Non-Endemic	Low	No data	N/A
Griselinia lucida	Puka	Tree	Indigenous Endemic	Low	No data	N/A
Macropiper excelsum	Kawakawa, Pepper tree	Tree	Indigenous Non-Endemic	Low	No data	N/A
Pseudopanax crassifolius	Horoeke, Lancewood	Tree	Indigenous Endemic	Low	No data	N/A
Solanum aviculare	Poroporo	Shrub	Indigenous Non-Endemic	Low	No data	N/A
Aristotelia serrata	Makomako/wineberry	Tree	Indigenous Endemic	Low/Moderate	Low/Moderate	Agreement
Coprosma arborea	Mamangi	Tree	Indigenous Endemic	No data	Low/Moderate	N/A
Melicytus ramiflorus	Mahoe, whiteywood	Tree	Indigenous Non-Endemic	Low/Moderate	Low/Moderate	Agreement
Myoporum laetum	Ngaio, mousehole tree	Tree	Indigenous Endemic	Low/Moderate	Low/Moderate	Agreement
Ripogonum scandens	Supplejack	Lianes (Vine)	Indigenous Endemic	No data	Low/Moderate	N/A
Sophora microphylla	Kowhai	Tree	Indigenous Endemic	No data	Low/Moderate	N/A
Cordyline australis	Ti kouka, Cabbage tree	Tree	Indigenous Endemic	Low/Moderate	Moderate	Agreement
Pittosporum crassifolium	Karo	Tree	Indigenous Endemic	Low/Moderate	Moderate	Agreement

Botanical name	Maori/European name	Plant Form	Native/Exotic	Field Flammability (Fogarty 2002)	Lab Flammability (Wyse et al. 2016)	Comparison
Pittosporum eugenioides	Tarata, Lemonwood	Tree	Indigenous Endemic	Low/Moderate	Moderate	Agreement
Knightia excelsa	Rewarewa, NZ honeysuckle	Tree	Indigenous Endemic	Low/Moderate	Moderate/High	Agreement
Weinmannia racemosa	Kamahi	Tree	Indigenous Endemic	Low/Moderate	Moderate/High	Agreement
Lophozonia menziesii (Syn. Nothofagus menziesii)	Tawhai, Silver beech	Tree	Indigenous Endemic	Low/Moderate	High	Field Lower
Coriaria arborea	Tutu	Tree	Indigenous Endemic	Low/Moderate	No data	N/A
Hebe salicifolia	Koromiko	Shrub	Indigenous Non-Endemic	Low/Moderate	No data	N/A
Hebe stricta	Koromiko	Shrub	Indigenous Endemic	Low/Moderate	No data	N/A
Hoheria spp	Houhere, Hoheria, Lacebark	Tree	Indigenous Endemic	Low/Moderate	No data	N/A
Melicytus lanceolatus	Mahoe wao	Tree	Indigenous Endemic	Low/Moderate	No data	N/A
Phyllocladus glaucus	Toatoa	Tree	Indigenous Endemic	Low/Moderate	No data	N/A
Plagianthus regius	Manatu, Ribbonwood	Tree	Indigenous Endemic	Low/Moderate	No data	N/A
Agathis australis	Kauri	Tree	Indigenous Endemic	Moderate	Low/Moderate	Field Higher
Beilschmiedia tarairi	Taraire	Tree	Indigenous Endemic	No data	Moderate	N/A
Beilschmiedia tawa	Tawa	Tree	Indigenous Endemic	Moderate	Moderate	Agreement
Fuscospora fusca	Red beech	Tree	Indigenous Endemic	No data	Moderate	N/A
Metrosideros excelsa	Pōhutukawa, New Zealand Christmas tree, Iron tree	Tree	Indigenous Endemic	No data	Moderate	N/A
Metrosideros fulgens	Forest liana, Climbing rata	Lianes (Vine)	Indigenous Endemic	No data	Moderate	N/A
Olearia traversiorum	Chatham Island akeake, or Chatham Island tree daisy	Tree	Indigenous Endemic	No data	Moderate	N/A
Pinus radiata (Syn. Pinus insignis)	Monterey pine, insignis pine or radiata pine	Tree	Exotic	No data	Moderate	N/A
Pittosporum tenuifolium	Kohuhu	Tree	Indigenous Endemic	Moderate	Moderate	Agreement
Prumnopitys ferruginea	Miro	Tree	Indigenous Endemic	No data	Moderate	N/A
Vitex lucens	Pūriri	Tree	Indigenous Endemic	No data	Moderate	N/A
Dacrydium cupressinum	Rimu	Tree	Indigenous Endemic	Moderate	High	Field Lower
Metrosideros umbellata	Southern Rātā	Tree	Indigenous Endemic	Moderate	No data	N/A

Botanical name	**Maori/European name**	**Plant Form**	**Native/Exotic**	**Field Flammability (Fogarty 2002)**	**Lab Flammability (Wyse et al. 2016)**	**Comparison**
Podocarpus dacrydioides	Kahikatea, White pine	Tree	Indigenous Endemic	Moderate	No data	N/A
Pterophylla sylvicola (Weinmannia silvicola)	Tawhero, Towhai	Tree	Indigenous Endemic	Moderate	No data	N/A
Phormium tenax	Flax	Graminoid	Indigenous Endemic	Moderate/High	Low	Field Higher
Dodonaea viscosa	Ake ake	Tree	Indigenous Non-Endemic	Moderate/High	Moderate	Field Higher
Sphaeropteris medullaris (Syn. Cyathea medullaris)	Mamaku, black tree fern	Tree Fern	Indigenous Non-Endemic	Moderate/High	Moderate	Field Higher
Cupressus macrocarpa	Monterey cypress	Tree	Exotic	No data	Moderate/High	N/A
Cyathea dealbata	Silver fern	Tree Fern	Indigenous Endemic	Moderate/High	Moderate/High	Agreement
Discaria toumatou	Matagouri, Tūmatakuru, Wild Irishman	Tree	Indigenous Endemic	No data	Moderate/High	N/A
Fuscospora cliffortioides	Mountain beech	Tree	Indigenous Endemic	No data	Moderate/High	N/A
Leucopogon fasciculatus	Tall mingimingi	Shrub	Indigenous Endemic	No data	Moderate/High	N/A
Olea europaea	Olive	Tree	Exotic	No data	Moderate/High	N/A
Olearia furfuraceae	Tree daisy	Tree	Indigenous Endemic	No data	Moderate/High	N/A
Phyllocladus trichomanoides	Tānekaha, Celery pine	Tree	Indigenous Endemic	No data	Moderate/High	N/A
Podocarpus totara	Totara	Tree	Indigenous Endemic	Moderate/High	Moderate/High	Agreement
Pteridium esculentum	Bracken fern, Austral bracken, Bracken	Fern	Indigenous Non-Endemic	No data	Moderate/High	N/A
Syzygium smithii	Common Lilly pilly	Tree	Exotic	No data	Moderate/High	N/A
Dicksonia squarrosa	New Zealand tree fern, Whekī, Rough tree fern	Tree Fern	Indigenous Endemic	Moderate/High	High	N/A
Cyathodes fasciculata	Mingimingi	Shrub	Indigenous Endemic	Moderate/High	No data	N/A
Phormium cookianum	Flax, harakeke	Graminoid	Indigenous Endemic	Moderate/High	No data	N/A
Kunzea ericoides	Kānuka, White tea tree	Tree or Shrub	Indigenous Endemic	High	Moderate/High	Field Higher
Alectryon excelsus	Tītoki, New Zealand oak	Tree	Indigenous Endemic	No data	High	N/A
Corokia buddleioides	Korokio	Shrub	Indigenous Endemic	No data	High	N/A

Botanical name	**Maori/European name**	**Plant Form**	**Native/Exotic**	**Field Flammability (Fogarty 2002)**	**Lab Flammability (Wyse et al. 2016)**	**Comparison**
Dracophyllum acerosum	Dragon leaf	Shrub	Indigenous Endemic	No data	High	N/A
Eucalyptus viminalis	Manna gum	Tree	Exotic	No data	High	N/A
Hakea sericea	Prickly hakea	Shrub	Exotic	No data	High	N/A
Leptospermum scoparium	Mānuka, Kahikātoa, Mānuka myrtle, New Zealand Teatree, Broom tea-tree, Tea tree	Tree or Shrub	Indigenous Non-Endemic	High	High	Agreement
Melaleuca linearis (Syn. Callistemon rigosum)	Bottlebrush	Shrub	Exotic	No data	High	N/A
Nestegis lanceolata	Maire	Tree	Indigenous Endemic	No data	High	N/A
Pomaderris kumaraho	Kumarahou	Shrub	Indigenous Endemic	No data	High	N/A
Ulex europaeus	Gorse	Shrub	Exotic	No data	VeryHigh	N/A

*Data was collected as part of this from fire managers.

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Appendix 2 Fire Hazard and Risk Tied to Insects and Diseases

Current and potential future insects and diseases that impact forests and how the impacts translate to forest stress, which can then be linked to fire hazard and risk.

Appendix 2 was developed using references identified from Jones at al. 2023 and Scion 2023, it is important to note that references that were not incorporated into these papers were not evaluated for Appendix 2. Insects and disease can cause widespread forest mortality, significantly changing the stand structure, composition, and fuel load over time. Any insect or disease that creates fuel accumulation (such as defoliation or branch lost), increases fuel flammability (resin-soaked branches, dead needles, witch's broom (deformity in the wood), dead stems, etc.) and thus represents a fire hazard. The Phases of forest stress include 1) Stressed Canopy, 2) Partial or full loss of canopy foliage, 3) tree mortality, 4) stand mortality (Table 3 in the main paper describes each of these phases in detail and links the impact to fuel hazard and potential fire behaviour).

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Native Forests	Disease	Kauri dieback (*Phytophthora agathadicida* (B.S. Weir, Beever, Pennycook & Bellgard))	Kauri [*Agathis australis* (D.Don) Lindl.]	One of the most important diseases affecting indigenous species. *P. agathadicida* has been reported in many locations across the native range of kauri. Phytophthora species cause fine root rot, foliage blights and casts that reduce productivity to stem cankers and tree mortality.	All Stages	3	Yes	No	(8, 9)
Native Forests	Disease	ten Phytophthora species (not Phytophthora agathadicida)	Tōtara [*Podocarpus totara* D.Don]	Phytophthora species cause various diseases, from fine root rot and foliage blights and casts that reduce productivity to stem cankers and tree mortality. *Phytophthora podocarpi* has been associated with foliage blight and twig dieback of tōtara	All Stages	3	Yes	some specie s are native	(9, 20)
Native Forests	Insect	ambrosia beetle (*Platypus apicalis* (White))	Beech species [*Nothofagus* spp.]	Mass attack of host trees and large-scale mortality	All Stages	1	Yes	Yes	(1)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Native Forests	Insect	polyphagous shot hole borer *(Euwallacea fornicatus* (Eichhoff))	Generalist	Highly invasive ambrosia beetle that attacks >400 plant species globally and has recently invaded Western Australia. It has reportedly killed hundreds of thousands of trees across riparian ecosystems	Late, Old Growth	3	No	No	(4)
Native Forests	Insect	sap sucking scale insect (*Acanthococcus orariensis (Hoy*))	Mānuka [*Leptospermum scoparium* JR Forst & G. Forst]	Kills large areas of mānuka. Plants infested have layers of sooty mould which induce accelerated tip growth before plant death. The 1st symptom of impending death is gradual browning of the canopy foliage, followed by rot at ground level and collapse of the plants.	?	3	Yes	No	(2, 3)
Native Forests	Insect + Disease	Rapid ohia death (pathogen *Ceratocystis lukuohia* (I. Barnes, T.C. Harrin. & L.M. Keith and *C. huliohia* I. Barnes, T.C. Harrin. & L.M. Keith)), along with ambrosia beetles (Xyleborus spp., Xylosandrus spp., and Xyleborinus saxesenii (Ratzeburg))	Metrosideros trees species in Hawaii could impact Pōhutukawa [*Metrosideros excelsa]*	The pathogens disperse faster while being transported by ambrosia beetles. Both Ceratocystis fungi colonize the sapwood of trees, clogging water transport resulting in death.	All Stages	3	No	No	(21)

Forest Type	**Insect Pest or Disease**	**Species**	**Target Forest Species**	**Description on forest health**	**Seral Stage**	**Phase of forest stress**	**Found in NZ**	**Native to NZ**	**Reference**
Native and Exotic Forests	Disease	Junghuhnia root rot (*Physisporinus vinctus* (Berk., Murrill))	Radiata pine and Kauri	Symptoms include yellowing of needles followed by browning in irregular patterns, along with resin, occasional cankers on the roots, and white/pink fungal pads at the soil level. Mortality can occur, more commonly in trees under five years, however, overall mortality of trees is low	Early, Mid	2	Yes	?	(32, 33)
Native and Exotic Forests	Disease	Myrtle rust (Austropuccinia psidii (G. Winter, Beenken))	Wide range of tree species, indigenous species of Myrtaceae, including *Lophomyrtus* spp., *Metrosideros* spp., Mānuka and 11 eucalypt species	Affects younger growing tissues (buds, stems, flowers, and fruits) leading to severe infection, necrosis and dieback of infected tissues. Following wildfire regenerating trees can become infected with minor leaf spots to repeated dieback of epicormic shoots leading to eventual death of the entire tree. One of the most impactful diseases affecting indigenous species where Lophomyrtus spp. are highly susceptible and facing localised extinction.	Early	3	Yes	No	(10, 11, 12, 13, 14, 15, 16, 17, 18, 19)
Native and Exotic Forests	Disease	Peniophora root and stem canker (*Gloeopeniophorella sacrata* (G. Cunn))	Radiata pine and Mānuka	Outbreaks often occur in slowly expanding disease circles, likely due to the primary infection pathway of root contact. Slow rate of mortality: Discolouration of the foliage accompanied by root collar cankers and eventually death.	Early, Mid	3	Yes	Yes	(34)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Native and Exotic Forests	Disease	root-infecting honey fungus species (*Armillaria aotearoa* Hood & Ramsfield, *A. limonea* (G. Stev.) Boesew and *A. novae-zelandiae* (G. Stev., Boesew))	Beech, Pittosporum, Weinmannia racemosa, and pine species	Greater impact to exotic species compared with native. It produces discolouration of needles to yellow then red, following mortality. Once Armillaria is present within a site, it is very difficult to eradicate	Early, Mid	2, 3	Yes	Yes	(5, 6, 7)
Native and Exotic Forests	Insect	endemic common forest looper *(Pseudocoremia suavis (Butler))*	Radiata pine, Southern Beech, Podocarps, and Kānuka [*Kunzea ericoides (*A. Rich.*)* J. Thompson]	Causes loss of needles, severe defoliation leading to decreased growth and death	All Stages	3	Yes	Yes	(25, 26)
Exotic forests	Disease	Barron Road syndrome (Fungal complex including *Thyrinula eucalyptina* (Petr. & Syd.) and *Teratosphaeria cryptica* (Cooke, Crous & U. Braun))	Ash eucalypts	Leaf and twig dieback, defoliation. Sporadic mortality, increases susceptibility to other diseases	All Stages	3	Yes	No	(1)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Disease	black stain root disease (*Leptographium wageneri ((*Kendr.*)* Wingf.*))*- 3 strains	Lodgepole pine (*Pinus contorta* Dougl. ex. Loud), Ponderosa pine (*Pinus ponderosa* Laws.), and Douglas-fir	Potentially lethal. Recently burned forests are more vulnerable to this disease.	Early, Mid	3	Yes	No	(47, 48)
Exotic forests	Disease	*Diplodia shoot dieback (Diplodia sapinea (*(Fr.) Fuckel))	Radiata pine	Reduced growth rate, malformed leaders, wood defects and shoot dieback	Early, Mid	2	Yes	No	(35, 36, 37)
Exotic forests	Disease	dothistroma needle blight (DNB) ((*Dothistroma septosporum* (Dorog.) M. Morelet))	Pine species	Premature needle drop, growth reduction, in some cases mortality	Early, Mid	2, 3	Yes	No	(43, 44, 45)
Exotic forests	Disease	gum emperor moth larvae (*Opodiphthera eucalypti* (Scott))	Ash eucalypts	Seedling defoliation	Early	2	Yes	No	(1)
Exotic forests	Disease	leaf blotch fungus (*Teratosphaeria cryptica*, and *T. nubilosa (Cooke, Crous & U. Braun))*	*E. nitens, E. regnans* and *E. fastigata*	Produces blotches and premature leaf abscission. Can be destructive in nurseries and is one of the most important diseases of eucalypt plantations in Australia and South Africa. Outbreaks in NZ as well	All Stages	2	Yes	No	(68, 67, 69)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Disease	*leafrollers (Strepsicrates macropetana* (Meyrick *and S. infensa* Meyrick))	Ash eucalypts [*Eucalyptus fastigata* (D. & M.)], and [*E. regnans* (F. Muell)].	Feed on growing tips causing significant defoliation in recently planted trees	Early	2	Yes	No	(49)
Exotic forests	Disease	Nectria flute canker (NFC) (*Corinectria fuckeliana (C. Booth, C. González & P. Chaverri))*	Radiata pine in New Zealand, but also *Picea* spp. and sometimes *Abies* spp.	Causes infection at wound sites - is often associated with tree pruning.	Late, Old Growth	1	Yes	No	(38, 39)
Exotic forests	Disease	*Red needle cast (RNC) (Phytophthora pluvialis* or *Phytophthora kernoviae)*	Radiata pine in New Zealand and Douglas-fir in America	Browning/reddening of leaves, defoliation and in the worst cases reduced growth of trees	All Stages	2	Yes	No	(40, (41, 42)
Exotic forests	Disease	Target spot or Corky spot (*Thyrinula eucalyptina)*	*E. regnans, E. fastigata, E. globulus,* and *E. nitens*	Circular necrotic lesions on upper and lower leaf surface, could cause severe infection in relatively young leaves and premature defoliation	All Stages	2	Yes	No	(65, 66, 67)
Exotic forests	Insect	Australian tortoise beetle (*Trachymela tincticollis (*Blackburn))	*Eucalyptus regnans* in NZ but over 12 other species in different countries.	Defoliation in trees, causing slower diameter increment and decrease in survival	Early, Mid	2	Yes	No	(56, 1, 57)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Insect	Bronze bug (*Thaumastocoris peregrinus* (Carpintero & Dellapé))	*E. globulus*, *E. macarthurii*, *E. viminalis* and *E. nitens*	Feeds on leaves which causes yellowing and leaf loss	Early, Mid	2	Yes	No	(63, 64)
Exotic forests	Insect	Eucalyptus snout weevil *(Gonipterus platensis (*Marelli*)*)	*Eucalyptus nitens,* and *E. globulus*	Leaf feeding insect resulting in crown defoliation and potential for yield loss	Early, Mid	2	Yes	No	(59, 1)
Exotic forests	Insect	Eucalyptus tortoise beetle *(Paropsis charybdis)*	*Eucalyptus nitens, E. fastigata, E. globulus* (Labill)*, E. macarthurii* (Dean & Maiden) and *E. viminalis* (Labill)	Long term, repeated defoliation causes crown dieback, and can cause death in young trees over a period of two years. Can result in a 50% loss of growth.	Early, Mid	2, 3	Yes	No	(58)
Exotic forests	Insect	gall wasps (e.g. the leaf blister sawfly *Phylacteophaga froggatti (*Rieck), and *Ophelimus eucalypti (*Gahan))	*Eucalyptus nitens*	Causes leaf drop of young leaves	Early, Mid	2	Yes	No	(60, 61, 62, 1)
Exotic forests	Insect	greenhouse thrip (*Heliothrips haemorrhoidalis* (Bouche*))*	Radiata Pine and Ash eucalypts	Causes seedling mortality	Early	3	Yes	No	(1)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Insect	Gum leaf skeletonizer (*Uraba lugens* (Walker))	*Eucalyptus camaldulensis* (Dehn.), *E. nitens* (Deane & Maiden), and Myrtaraceae species	Attack is usually heaviest in the outer three to four rows of young trees in plantations, and between 3% and 17% tree mortality has been recorded following two seasons of heavy defoliation. Biological control methods and tree thinning in plantation forests have minimised the outbreak risk in NZ	Early, Mid	3	Yes	No	(50, 51, 52, 53, 54, 55, 1)
Exotic forests	Insect	Monterey pine aphid (*Essigella californica* (Essig))	In New Zealand, Radiata pine is the most common host, but also *Pinus muricata* (D.Don), *Pinus michoacana* (Martinez) and Douglas-fir [*Pseudotsuga menziesii* Mirb.) (Franco)]	Causes needle yellowing and premature shedding. In Australia, it has caused severe crown damage	All Stages	2	Yes	No	(27, 28)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Insect	Other tortoise beetle species (*Paropsisterna beata* (Newman), *Paropsisterna (cloelia Stal), Trachymela catenata (Chapuis,* and *T. sloanei Blackburn*))	*Eucalyptus nitens,* and *E. globulus*	Defoliation in trees	Early, Mid	2	Yes	No	(1)
Exotic Forests	Insect	pine bark beetle (*Hylastes ater (*Paykull))	mainly Radiata pine [*Pinus radiata* D.Don] and *Pinus sylvestris* L.	Attacks the bark of recently planted (young) trees, increasing their mortality rates	Early	3	Yes	No	(22)
Exotic forests	Insect	pine feeding adelgids (*Pineus boerneri* (Annand))	reported in Radiata pine in New Zealand but also in *P. kesiya* (Royle ex Gordon*), P. tecunumanii* (Schwerdtf), *P. maximinoi* (HE Moore), *P. oocarpa* (Schiede), *P. resinosa* Ait. in other countries	Sapsuckers cause defoliation and stunted growth	All Stages	2	Yes	No	(29, 30)

Forest Type	Insect Pest or Disease	Species	Target Forest Species	Description on forest health	Seral Stage	Phase of forest stress	Found in NZ	Native to NZ	Reference
Exotic forests	Insect	pine feeding adelgids (*Pineus pini (*Macquart))	reported in Radiata pine in New Zealand but over 40 other species of pines around the world	Sapsuckers cause defoliation and stunted growth	All Stages	2	Yes	No	(31, 30)
Exotic forests	Insect + Disease	ambrosia beetles + stain fungi	Douglas-fir	Attack fire-killed trees - enhancing deterioration of fire-killed timber by introducing stain fungi	Late, Old Growth	1, 2	Yes	No	(46)
Exotic Forests	Insect + Disease	pine-killing woodwasp (*Sirex noctilio* Fabricius*)* infects trees with the patchy duster fungus (*Amylostereum areolatum (Chaillet ex Fr., Boidin)*	most pine species, but mainly has affected Radiata pine in New Zealand.	It is the only known woodwasp species to be capable of killing trees. Usually attacks trees stressed by drought resulting in death of the trees after attack.	All Stages	3	Yes	No	(23, 24)

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