How flammable is your farm? Measuring the flammability of crops and pastures, and other plant species commonly found on farms in Canterbury, New Zealand

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Due to human-induced climate change, global temperatures are expected to rise, leading to increased extreme fire weather being predicted for New Zealand (NZ). Destructive fires are becoming more prevalent every year, threatening our biodiversity, and causing damage to human infrastructure, crops, and pastures. Hence, NZ's landscapes must be made more resilient to wildfires. One potential tool to help reduce fire spread is green firebreaks, strips of low flammability vegetation that are strategically placed across the landscape. However, to establish green firebreaks, we first need to know the flammability of different species. While there has been some research examining the flammability of introduced and native trees, shrubs, and grasses in NZ, there is a lack of information regarding the flammability of common crops and pasture grasses used not only in NZ, but around the world. This thesis intends to address this knowledge gap by testing the shoot flammability of common pastures, crops and other plant species that occur on Canterbury farms. This thesis also compares the flammability of these crop and pasture species to that of other plant species already tested in NZ to produce a list of low flammability species which can be used to develop potential green firebreaks on farms in NZ and other temperate regions of the world where similar crops are grown.

The shoot-level flammability of 47 common NZ crop and pasture species found on rural Canterbury farms was tested and most of these species were found to be of Low or Very Low flammability. Only three of the species, Common pear (*Pyrus communis)* and two Apple varities (*Malus domestica* var. Braeburn, *M. domestica* var. Royal Gala) were of Very High flammability, indicating that many crop and pasture species grown in Canterbury are suitable to use as green firebreaks. These 47 crop and pasture species were then compared to 269 other plant species already tested in NZ and found to be comparatively very low in flammability, further suggesting that crop and pasture species are excellent candidates for green firebreaks on agricultural and rural land. This supports recent suggestions that diversified agricultural systems can lower the likelihood of large, intense fires and will assist farmers and landowners in redesigning their farms so they can plant low-flammability species in areas they deem to be high fire dangers. Overall, this knowledge will improve our understanding of how fire regimes change over time and space in agricultural landscapes and help mitigate wildfires in an era of rapid climate change and increasingly destructive wildfires in NZ and around the world.

Keywords: plant flammability, fire, pasture, crops, farms, green firebreaks, climate change.

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Chapter 1

General Introduction

Due to human-induced climate change, global temperatures are expected to rise, and severe fire weather is predicted to increase in many parts of New Zealand (NZ) (IPCC, 2022). The devastating effects of wildfires have been seen in the 2019/2020 Black Summer Australian bushfires (Abram et al., 2021) and the 2018 (Syphard and Keeley, 2019) and 2020 Californian wildfires (Keeley and Syphard, 2021), but also in recent severe wildfires in NZ, including the Port Hills in 2017 (Pearce, 2018), and Lake Pukaki and Lake Ohau in 2020 (Fire and Emergency NZ (FENZ), 2020). Pre-historically, natural fire activity in NZ was relatively infrequent (Guild and Dudfield, 2009; Perry et al. 2014), with charcoal records representing fires once or twice per millennium (Bowman and Haberle, 2010). The arrival of humans in NZ resulted in the transformation of predominantly forest landscapes to grassland and shrubland, along with associated soil changes and has altered NZ's fire regimes both temporally and spatially (McWethy et al., 2010). Fire is now not only more frequent than in the past, but it also operates in landscapes that are fragmented and hence relatively smaller, making wildfires effectively larger (Perry et al., 2014).

The severity of fires in NZ has also been increased by the presence of highly flammable invasive plants, such as gorse (*Ulex europaeus*), pines (*Pinus* spp.), and *Hakea* spp. (Perry et al., 2015; Wyse et al., 2016). These changing patterns of fire require innovative solutions to help ensure the resilience of NZ landscapes and primary industries (agriculture, horticulture, and forestry) in an increasingly fire-prone world. One potential option to reduce fire spread is green firebreaks, strips of low flammability vegetation, which are established at strategic points across the landscape (Cui et al. 2019). Green firebreaks have been widely used throughout the world, including in NZ. If these strips are comprised of native species of low flammability, they will not only aid in fire management but may also aid in the conservation of native biodiversity. There is also the potential for food crops or pastures to serve as green firebreaks, as demonstrated in Brazil (Xaud et al., 2009), Canada (Baxter and Woosaree, 2013), and New Zealand (Jolly and Guild, 1974), but to date there has been no large-scale screening of the flammability of crop and pasture species to identify low flammability species suitable to be used as green firebreaks in agricultural landscapes.

Agricultural exports in NZ are a major contributor to the country's economy, wherein agricultural products contributed to 70 percent of total merchandise exports for NZ in 2014 (Ministry for Primary Industries, 2017); and the demand for exports will increase with the rising human population. However, given the current and predicted global environmental changes, agricultural practices around the world are changing, and increasingly fire is a major threat to agricultural industries (Moreira and Pe'er, 2018). My research proposes to test the flammability of common crops and other plant species that typically occur on rural land. I will first identify the crop and pasture species commonly found on some Canterbury farms and collect shoot samples from the selected species and then test their flammability using a standard burning apparatus. Findings from my study can then be used in the development of green firebreaks to halt the fire spread across rural landscapes.

1.1 Importance of studying wildfires

While catastrophic fires have occurred in the past, the frequency of these events has dramatically escalated during the dawn of the twenty-first century (Keeley and Syphard, 2019), as a result of human-caused climate change and land-use changes (Bowman et al. 2017a). The Australian Black Summer bushfires of 2019/2020 and the California wildfires of 2020 are prime examples of the effects of climate change on fire weather (Goss et al. 2020; Abraham et al. 2021; Higuera and Abatzoglou, 2021; Reddy et al. 2021; Touma et al. 2021). Extreme fire seasons like these raise serious concerns about ecological communities' ability to adapt to climate-driven changes in fire regimes. Besides, fires can have devasting impacts on major infrastructures and assets, communities, homes, agriculture, and human health (Belcher et al., 2021). For example, the 2019/2020 Australian fires affected approximately 12.6 million hectares of land, killed approximately three billion wild animals, and destroyed many people's homes and livelihoods (Legge et al., 2022; Wintle et al., 2020). In the UK, during a heat wave in early July 2018 (i.e., >25˚C), a 'small' fire (30 hectares burned) broke out in a corn field cut by a combine harvester, quickly spreading across both cut and standing crops (Belcher et al., 2021), considerably impacting nearby residential homes, commercial properties and also disrupting travel. Additionally, inhaling smoke from a wildfire may be a serious health hazard since it is composed of carbon dioxide, carbon monoxide, particulate matter, nitric oxide, and other harmful compounds (Grant and Runkle, 2022). These are just a few examples of the many disruptions that a widespread fire could result in.

Though fires were relatively rare in NZ prior to the arrival of humans (Guild and Dudfield, 2009; Perry et al. 2014), predictions of increased very high and extreme fire weather for the country (Pearce and Clifford, 2008; Watt et al., 2019) emphasizes the importance of fire management now more than ever. Furthermore, a series of recent, large, and destructive bushfires, such as the 2017 Port Hills fire (Pearce, 2018), Nelson bushfire (Huggins et al., 2020), Middlemarch fire (Christensen et al., 2021), Lake Pukaki scrub and Lake Ohau forest fires (FENZ, 2020) has demonstrated the cost of extreme wildfires in NZ (Pearce, 2018).

1.2 Fire regimes, spread and risk

The palaeoecological record documents major environmental changes associated with human settlement in NZ, such as higher macro-charcoal in the sediment records in the South Island lakes, which depict an "initial burning period" (IBP) (McWethy et al., 2010). The IBP is defined as the “large increase in fire activity that occurred soon after first known Māori presence” (McWethy et al., 2009). During the IBP, huge areas (mostly drier lowland forests) were extensively burned (McWethy et al., 2010). More than 40% of the current forest cover appears to have been burned during the IBP, with nearly all lowland and montane dry forest receding (McGlone, 1983; McWethy et al., 2009). Wetter upland forest (e.g., dominated by *Fuscospora* and *Lophozonia*) was less affected, but this is more likely due to landscape location (in wetter climates and microclimates) than an underlying lack of sensitivity (Perry et al., 2014). As a result, some montane and lowland dry podocarp–hardwood forest types have become endangered (McGlone, 2001). During this time, the fire regimes went through significant changes wherein not only did the fires become more frequent, but they also became more spatially correlated (Perry et al., 2014).

Fire regimes are the patterns of fire activity across space and through time (Turner, 2010), and are characterised by variables, such as fire frequency, intensity, seasonality of occurrence and the type of fire (i.e., if the fire is above or below the ground; Gill (1975)). Fire regimes have been altered by humans through land-use changes related to forestry, urbanization, and agriculture, wherein fires are intentionally started or suppressed particularly in agricultural land, which may influence biodiversity and ecosystems in the surrounding landscape (Kelly et al. 2020). In New Zealand, changes in fire regimes and biodiversity between 2000-2019 were found to be due to land use change and biotic mixing (mixing of plant species between invasive and native species) (Perry et al., 2015). These complicated interactions between fire, climate, vegetation, and humans, make it difficult to determine cause and effect and understand how future climate and human actions will affect fire regimes on local to global scales.

Climate change in NZ is predicted to result in drier, windier, and warmer conditions, and cause increased drought periods (Pearce and Kerr, 2010; Langer et al., 2021), particularly in eastern areas of the country. The wind can play an important role in fire intensity and spread (Pollet and Omi, 2002) and is crucial to consider when assessing fire management strategies. In the field of fire ecology, wind is often referred to as ‘ambient wind’ and it supposedly has two contradictory effects on fire: it either increases fire severity by contributing more oxygen, or it cools a fire by eliminating and diluting combustible gasses (Chen et al. 2008). It is widely assumed that the rate of spread of fire increases when wind is present, but the effects of wind on a spreading fire are not well understood. Moreover, increased wind and solar radiation results in a dry microclimate which affects fuel moisture, contributing to more severe fire behaviour (Pollet and Omi, 2002). Nevertheless, some studies show that warm and dry north-westerly winds may cause extreme fire danger (Sharples et al. 2010), which is often observed in eastern South Island (Jane, 1986). A possible reason for this may be that when winds blow from the north or northwest directions, there is a sudden increase in temperature and a drop in humidity, which favour a widespread fire (Sharples et al. 2010).

Fire spread is influenced by many factors. While it is important to consider the flammability of individual species, fire spread is often influenced by the composition and structure of species in the whole community (Pausas et al. 2017). Moreover, topography affects fire behaviour, wherein the fire moves faster up slopes due to the geometry of the landscape (Beer, 1991). Multiple ignition sources may also contribute to fire spreading across a landscape (Gill and Allan, 2008). Farms are especially susceptible to multiple ignition sources due to a high presence of machinery, human movements, and dry grasses as well as suitable weather conditions. Hence, the agricultural areas (both cropping and pastures) of the eastern parts of NZ are likely to experience more destructive fires in the future. While there have been a few studies measuring fire behaviour in crops (Cheney and Sullivan 2008), my study is the first of its kind that seeks to address how fire regimes on farms might be moderated by manipulating existing agricultural systems. This project aims to determine which cropping and pasture species are low in flanmmability and hence can be planted to help reduce fire hazard.

1.3 New Zealand fire history

Prior to human settlement, natural fire activity was relatively low in NZ and even when they did occur, fires were mostly in lowland wetland habitats (Guild and Dudfield, 2009; Perry et al. 2014; Williams, 2009) wherein the ignition sources were often lightning and volcanoes (Guild and Dudfield, 2009; Williams, 2009). Volcanic activity is said to be the most common ignition source in the central and northern parts of the North Island, while the South Island's natural fire ignition sources were lightning strikes or coal and lignite combustion (Williams, 2009). The rarity of fire occurrence is evidenced by the lack adaptations among NZ's native flora to survive fire (Battersby et al. 2017). However, post-colonization, fires were used by both Māori (the indigenous people of Aotearoa New Zealand) and Pākehā (European New Zealanders) to modify the natural terrain in order to make space for cultivation and settlement (Beaglehole, 2012; Guild and Dudfield, 2010).

Early Polynesian settlers significantly altered the environment on each of the islands they inhabited by using fire, primarily because they introduced fire into pre-human ecosystems in which fire was naturally rare (Fosberg, 1963). According to McGlone (1989), the arrival of Polynesians in NZ directly caused the extinction or decline of a large portion of the vertebrate species, the eradication of a significant amount of lowland and montane forests, and extensive soil erosion. When Polynesian settlers came to NZ, they brought with them an economy focused on horticulture, a significant portion of which was shifting cultivation using fire as a method for clearing forests (Kirch, 1991, cited in Williams, 2009). They also had strong belief systems and norms around fire's sacredness and usage (Williams, 2009). Fire was used as a land management tool by Māori to clear paths for movement and establishing community sites (Clifford et al., 2016) and was and may also have been used to hunt game birds and megafauna like the moa (Dinornithidae) by clearing shielding vegetative cover from them which drove them into more open areas (Holdaway and Jacomb, 2000). Moreover, the fire was also an important tool used to maintain bracken fern (*Pteridium esculentum*), a pioneer species, wherein burning promotes its growth (McGlone et al., 2005). This species was extensively grown by the Māori because the bracken rhizomes provided them with a vital source of carbohydrate in their diets (McGlone et al., 2005). Eventually, the colonization of Māori resulted in a transformation of large tracts of NZ's landscape from lush green forests to scrubland because they discovered that soils, where forests had been burned, were more productive for growing crops (Baillie and Bayne, 2019).

A second wave of forest loss occurred in NZ throughout the European era, with fire being the main tool used to remove forest, scrub, and fernland to make way for agricultural activity (Perry et al., 2014; Clifford et al., 2016). Early European fires were occasionally very large, lasting for days or even weeks, and destroying both new successional forests and older, less disturbed forests (Wardle 2001). It is estimated that around 3.3 million hectares of forest were burned during 1830-1873, following the expansion of European settlers (Beaglehole, 2012). Compared to the North Island, European burning was more widespread on the South Island. The majority of the high-country tussock lands in the areas of Nelson, Marlborough, Canterbury, Otago, and Southland had been transformed into major grazing runs by the late 1850s (O'Connor, 1982). European settlers used similar ignition and burning strategies to the Māori, lighting burns on days when the predominant wind was in the intended burning direction and occurred in the drier summer months after weeks of dry weather (Baillie and Bayne, 2019). Between 1861-1901, grass-covered land increased from 70,000 ha to 4.5 million ha (Beaglehole, 2012), significantly transforming the nature and character of NZ landscapes.

1.4 Green firebreaks: flammability traits and structure of green firebreaks

'Green firebreaks' are strips or layers of plant species with low flammability that are strategically placed around or across a landscape (Curran et al. 2018; Cui et al. 2019). When looking for low-flammability vegetation for green firebreaks, Murray et al., (2020) believed that three flammability traits in particular should be evaluated together: how long it takes a plant to ignite (ignitibility), how long it takes a plant to burn (sustainability), and how well it burns (combustibility). These three are intrinsic flammability traits that explain plants' basic burning properties. However, consumability (how much of a sample is burned) (Wyse et al., 2016) is also considered an important component of plant flammability. Plant flammability can also be measured using different parts of the plant such as leaves or needles, twigs (Dimitrakopoulos and Papaioannou, 2001; Kane, Varner, and Heirs, 2008; Owens et al., 1998), litter (Cornwell et al., 2015) or more recently, using whole shoots or whole plants (Jauguiberry et al. 2011; Wyse et al., 2018). Moreover, some functional traits that determine and influence the flammability of plants include moisture content, retention of dead materials and unstable organic compounds (Padullés Cubino et al., 2018). Overall, the flammability characteristics of an optimal low-flammability plant species would be related to one another in such a way that the species is slow to ignite, burns for a short duration, and combusts with low intensity.

The structure and density of a green firebreak play a crucial role in its effectiveness (Cui et al. 2019). Past studies have shown the firebreaks to be either single layered, wherein it typically consists of one species, particularly a tree species, or for it to be multi-layered which comprises a mixture of tree, shrub, or herbaceous species (Cui et al. 2019). Positioning of a green firebreak is also equally important as the aim of a firebreak is to isolate a fire and prohibit it from spreading (Cui et al. 2019). Moreover, using native species to implement green firebreaks is an exceptionally good conservation tool in NZ as not only does it reduce the risk of fires spreading across the landscape, but it also contributes towards biodiversity by providing food for native fauna, as well as increasing their habitat and dispersal opportunities (Curran et al. 2018) given the alarming rate of decline in native biodiversity (Ministry for the Environment and Stats NZ, 2022).

1.5 Managing fire on New Zealand agricultural landscapes

Historically, fire was only ever used as a land management tool in order to make space for pasture and increase agricultural productivity in NZ. Today, fire continues to be the most affordable and sustainable tool for rural landowners wherein it is utilised for a variety of land management techniques, such as clearing woody vegetation and crop remains and restoring pasture land (Clifford et al., 2016). But there are also dangers in using fire as a tool for land management, such as the possibility of controlled wildfires escalating from prescribed burns (Clifford et al., 2016), as well as possible effects on ecological and cultural features, non-renewable natural resources, biodiversity values, financial loss and infrastructure damage.

Moreover, 51 percent of NZ’s land area is used for agriculture and horticulture (Stats NZ, 2021a), with 13 percent of land being occupied as farmland (Stats NZ, 2021b). Though a substantial amount NZ’s land is involved in agriculture, there is little to no research regarding fire management strategies on farmland. While there have been some recent advancements in plant breeding and other conservation farming methods to increase yield and improve farming economics, it is equally important to acknowledge that they also result in extremely high fuel loads (Westcott, 2019). Given that climate change is contributing to higher temperatures and drier conditions, the possibility of fires is expected to rise across a wide range of landscapes (Abram et al., 2021; United Nations Environment Programme (UNEP), 2022), making the occurrence of wildfires on agricultural land a ‘when’ instead of an ‘if’. Hence, there is a massive knowledge gap in the area of fire management in agricultural landscapes.

1.6 Aim and Objectives

This thesis intends to address the knowledge gap mentioned above by setting out the following aims and objectives:

I. Identify the common pastures, crops and other plant species that may occur on Canterbury farms.
II. Test the shoot flammability of these plant species.
III. Identify low flammability crops to be used in green firebreaks on NZ farms.

Results from my study will enable farmers and landholders to redesign their farms, wherein they may be able to plant any low-flammability crops found in the study, in areas they deem as high fire hazards.

Chapter 2

Flammability of crops and pastures in Canterbury, New Zealand

2.1 Introduction

Agriculture is a major contributor to New Zealand's (NZ) economy, contributing to around $11 billion per annum, which is approximately 4% of the gross domestic product (GDP) (Pearson, 2020). One of the main agricultural regions in NZ is the Canterbury region, which contains 64 percent of NZ's irrigated agriculture (Ministry for the Environment and Stats NZ, 2021), and produces a majority of arable crops such as wheat, oats and peas (Stark and Gillespie, 2021). However, Canterbury is also the most fire-prone region in NZ, with four of the top five towns and cities in NZ for fire season length being found in this region (Rolleston, Christchurch, Rangiora, and Kaiapoi) (Langer et al., 2021). Hence, it is crucial that the flammability of common crops used in Canterbury is tested, so we can redesign agricultural land to reduce fire hazards and help protect the industries and livelihoods that rely on it.

While there are many studies that examine the flammability of species in NZ landscapes such as forests, shrublands and grasslands (Cui et al., 2020a; Cui et al., 2020b; Padullés Cubino et al., 2018; Wyse et al., 2016), there is a lack of research in flammability of species pertaining to agricultural and horticultural landscapes. This study will be the first to globally screen the flammability of a wide range of commonly planted crop and pasture species, which will enable farmers to not only protect their lands, but also identify ways in which fire management can be incorporated into farm planning, by using low-flammability crop or pasture species as green firebreaks.

Past events and research has shown that agricultural lands are generally less fire-prone when compared to other landscapes (Moreira et al., 2011; Nunes et al., 2005). This is possibly due to lower fuel loads on farms compared to other ecosystems, as fuel load is one of the major drivers of wildfires (Schwilk, 2015; Harris et al., 2016). However, some studies in Europe have identified agricultural fields as a major source of wildfire, largely due to a higher number of ignitions and ignition sources (Catry et al., 2009; Ganteaume et al., 2013). Moreover, in a recent study conducted by Viedema et al. (2018), the biophysical and human-related factors of wildfires were assessed in a rural area of Spain over the span of 29 years and showed that wildfires have begun moving from higher terrain consisting of conifers and other flammable species, to areas of lower elevations where herbaceous crops and larger farms are present. Despite observations of fires being less destructive on agricultural land given the lower fuel load in the past, Viedema et al., (2018) concluded that topographic variables contributed less significantly to explaining fire intensity in the last few decades, complicating the understanding of how fire regimes are changing in different landscapes.

Fires on agricultural land are responsible for 10% of the total number of fires that occurs worldwide (Korontzi et al., 2006) and threaten air quality, food security, economic growth, and public health, as well as the surrounding environments. These fires burn through various pastures, crops, weeds, orchards, and other vegetation on farms. An understanding of the flammability characteristics of crop and associated plant species will provide critical information on how to manage fires on farms. In this chapter, I examine patterns in species flammability across whole agricultural landscapes using NZ farms, particularly in Canterbury, as an example. This work will have broader applicability, as it will entail measuring the flammability of many crops commonly planted elsewhere in temperate regions.

2.2 Identification of crop and pasture species for use of green firebreaks

In the era of rapid climate change and Anthropocene, Kelly et al., (2020) mentioned that diversifying agricultural practices by implanting low flammability crops and other species is an emerging nature-based approach that can reduce the severity and intensity of fires, as well as benefiting biodiversity by providing an increased range of habitats. However, there has been very limited research in identifying crop and pasture species that can be used as green firebreaks. In a study by Xaud et al. (2009) in Roraima, Amazonia (Brazil), pineapple crops (*Ananas comosus*) were identified to be a good green firebreak. In this study, the researchers compared the characteristics of two types of pineapple cropping (traditional and dense plantings), with legumes such as *Desmodium ovalifolium* (Sweetheart or tropical clover) and *Arachis* sp. (Peanut) as firebreak hedgerows. In field trials, they found that the pineapple hedgerows were responsible for breaking the fire in both the traditional and dense treatments, due to anatomical traits that reduce water vapour losses and allow water absorption, thereby shielding itself from the fire intensity (Xaud et al. 2009). While this is a valuable discovery, it is mostly applicable to tropical farmlands where pineapple or these legumes are common crops.

Another study by Baxter and Woosaree (2013), which was conducted for several years in Canada, tested the flammability of Rocky Mountain fescue (*Festuca saximontana*), white clover (*Trifolium repens*), yarrow (*Achillea millefolium*) and other herbaceous species as well as some grass mixes. Initially, they found that white clover and yarrow stopped the fire abruptly, while the plots with grass mixes saw no change in fire behaviour when tested in single species plots (Baxter and Woosaree, 2013). However, in a later stage of the study they found that the three species (rocky mountain fescue, white clover, and yarrow) reduced fire behaviour, and in some treatments, the fire self-extinguished. This study did not assess the characteristics that made these plant species less flammable than others, but it does demonstrate the variable flammability of pasture mixes.

Moreover, an older study by Jolly and Guild (1974) in NZ found that Lucerne (*Medicago sativa*) made a good green firebreak, wherein they established New Zealand's first green firebreaks using this crop.

However, this study did not individually assess the flammability of lucerne, nor did it explain its fire behaviour. This highlights a major gap in knowledge regarding flammability of lucerne, as well as other pasture crops.

2.3 Canterbury Landscape and Climate

Central and eastern sections of southern NZ are generally subject to drying westerly winds and low precipitation. For example, the mean annual rainfall for central and eastern sections of southern NZ was 250 mm – 750 mm in 2019 (National Institute of Water and Atmospheric Research Ltd. (NIWA), 2020). The dry weather on the leeward side of NZ is intensified by a water deficit that often occurs between October and April, as well as strong prevailing winds, and decreased precipitation which increases the fire danger in this region (Williams, 2009). Around 3000 years ago, the El Nino Southern Oscillation intensified, and the climate became more favourable to fire, particularly in the drier eastern regions of both islands (Perry et al. 2014). Given that climate change in NZ is predicted to result in drier, windier, and warmer conditions, as well as causing increased drought periods (Pearce et al. 2011), and looking at the natural climatic patterns in Canterbury, the need to better understand the relationship between flammability and types of crops is reinforced.

Furthermore, Canterbury has previously been ranked the highest for regional fire climate severity with an average rank of 1.7, in a long-term fire climate study (Pearce and Clifford, 2008). This rank was based on an average of climate change scenarios, Cumulative Daily Severity Rating (CDSR) and the mean number of days of 'Very High' and 'Extreme' in forests and scrublands on the NZFDRS over 127 fire stations (Pearce and Clifford, 2008). Hence, the agricultural areas (both cropping and pastures) of the eastern parts of New Zealand are likely to experience fires that are more destructive in the future. This project aims to determine which cropping and pasture species can be planted to help reduce fire hazards.

2.4 Research Questions and Aims

In this chapter, I aim to quantify the shoot- or whole-plant flammability of common crops, pastures and weeds that occur on Canterbury farms.

2.5 Methods

2.5.1 List of species used in the study

The list of species to test in this study was compiled from several sources describing common crop and pasture species present on farmland in NZ. Data regarding common pasture grasses were collected from Charlton and Stewart (1999), wherein they collated a list of pasture species and cultivars used in New Zealand. The list of legumes, grazing herbs and catch crops (crops that 'catch' excessive nitrogen that might otherwise be lost through leaching) was collated from the DairyNZ website (DairyNZ, 2021), while the list of fruit and vegetable crops was compiled from Horticulture NZ Annual Reports from 2017-2020, and ranking crops based on their highest export values (in terms of millions of dollars exported; Horticulture NZ 2017; 2018; 2019; 2020; 2021). Similarly, the list of wine grapes was gathered by surveying the New Zealand Winegrowers Inc. Annual Report of 2020, based on the highest export value (in terms of millions of litres exported; New Zealand Wine, 2020). This list was then used to identify crop and pasture species available on the Lincoln University campus and nearby farms. Some species that were not on these lists were also sampled since they were readily available on farms in the area (barley, oats, olives, gooseberries, bell pepper, common mallow, common yarrow, and dock).

The final list comprised 47 taxa from 18 families, including cereal crops (4 taxa), forage crops (4 taxa), fruit trees and shrubs (7 taxa), grazing herbs (2 taxa), pasture grasses (8 taxa), pasture legumes (7 taxa), vegetables (5 taxa) and wine grapes (6 taxa; Table 1).

Table 1: Crop and pasture species included in this study. Taxonomy follows the New Zealand Plant Conservation Network (http://www.nzpcn.org.nz) and Royal Botanic Gardens Kew's Plants of the World Online (https://powo.science.kew.org/).

Crop Type	Species	Species Code	Scientific Name	Family Name
Cereal Crop	Barley	HORvul	*Hordeum vulgare* L.	Poaceae
Cereal Crop	Oats	AVEfat	*Avena fatua* L.	Poaceae
Cereal Crop	Popcorn	ZEAmay.Pop	*Zea mays* var. *everta*	Poaceae
Cereal Crop	Wheat	TRIaes	*Triticum aestivum* L.	Poaceae
Forage Crop	Fodder Beet	BETvul	*Beta vulgaris 'Mangelwurzel'*	Amaranthaceae
Forage Crop	Kale	BRAole	*Brassica oleracea* L. var. *Sabellica*	Brassicaceae
Forage Crop	Sweetcorn	ZEAmay	*Zea mays* var. *rugosa*	Poaceae
Forage Crop	Rapeseed	BRAnap	*Brassica napus* L.	Brassicaceae
Fruit	Apple Braeburn	MALdom.Bra	*Malus domestica.* 'Braeburn'	Rosaceae
Fruit	Apple Royal Gala	MALdom.Roy	*Malus domestica.* 'Royal Gala'	Rosaceae
Fruit	Barnea Olives	OLEeur.Bar	*Olea europaea. '*Barnea'	Oleaceae
Fruit	Blueberries	VACspp	*Vaccinium spp.*	Ericaceae
Fruit	Gooseberries	RIBuva	*Ribes uva-crispa* L.	Grossulariaceae
Fruit	Common Pear	PYRcom	*Pyrus communis* L.	Rosaceae
Fruit	Raspberries	RUBida	*Rubus idaeus* L.	Rosaceae
Grazing Herb	Chicory	CICint	*Cichorium intybus* L.	Asteraceae
Grazing Herb	Ribwort Plantain	PLAlan	*Plantago lanceolata* L.	Plantaginaceae
Pasture Grass	Cocksfoot	DACglo	*Dactylis glomerata* L.	Poaceae
Pasture Grass	Italian Ryegrass	LOLmul	*Lolium multiflorum* Lam.	Poaceae
Pasture Grass	Pasture Brome	BROval	*Bromus valdivianus* Phil.	Poaceae

Pasture Grass	Perennial Ryegrass	LOLper	*Lolium perenne* L.	Poaceae
Pasture Grass	Phalaris (Bulbous canary-grass)	PHAaqu	*Phalaris aquatica* L.	Poaceae
Pasture Grass	Prairie Grass	BROwil	*Bromus willdenowii* Kunth.	Poaceae
Pasture Grass	Tall Fescue	FESaru	*Festuca arundinacea* Schreb.	Poaceae
Pasture Grass	Timothy grass	PHLpra	*Phleum pratense* L.	Poaceae
Pasture Legume	Caucasian Clover	TRIamb	*Trifolium ambiguum* M.Bieb	Fabaceae
Pasture Legume	Coronilla (Crown vetch)	SECvar	*Securigera varia* (L.) Lassen	Fabaceae
Pasture Legume	Hairy canary-clover	DORhir	*Dorycnium hirsutum* L.	Fabaceae
Pasture Legume	Lotus (Big trefoil)	LOTped	*Lotus pedunculatus* Cav.	Fabaceae
Pasture Legume	Lucerne	MEDsat	*Medicago sativa* L.	Fabaceae
Pasture Legume	Red Clover	TRIpra	*Trifolium pratense* L.	Fabaceae
Pasture Legume	White Clover	TRIrep	*Trifolium repens* L.	Fabaceae
Vegetable	Californian Bell Pepper	CAPann	*Capsicum annum* L.	Solanaceae
Vegetable	Dwarf Snow Pea	PISsat	*Pisum sativum* L.	Fabaceae
Vegetable	Spring Onion	ALLfis	*Allium fistulosum* L.	Amaryllidaceae
Vegetable	Potatoes	SOLtub	*Solanum tuberosum* L.	Solanaceae
Vegetable	Squash	CUCspp	*Cucurbita spp.* L. (*maxima, moschata, pepo*)	Cucurbitaceae
Weed	Common Mallow	MALneg	*Malva neglecta* Wallr.	Malvaceae
Weed	Common Yarrow	ACHmil	*Achillea millefolium* L.	Asteraceae
Weed	Dock (broad-leaved)	RUMobt	*Rumex obtusifolius* L.	Polygonaceae
Weed	Fathen	CHEalb	*Chenopodium album* L.	Amaranthaceae
Winegrape	Chardonnay	VITvin.Cha	*Vitis vinifera.* 'Chardonnay'	Vitaceae
Winegrape	Merlot	VITvin.Mer	*Vitis vinifera*. 'Merlot'	Vitaceae
Winegrape	Pinot Gris	VITvin.Gri	*Vitis vinifera.* 'Pinot Gris'	Vitaceae
Winegrape	Pinot Noir	VITvin.Noi	*Vitis vinifera.* 'Pinot Noir'	Vitaceae
Winegrape	Riesling	VITvin.Rei	*Vitis vinifera.* 'Riesling'	Vitaceae
Winegrape	Sauvignon Blanc	VITvin.Sau	*Vitis vinifera.* 'Sauvignon Blanc'	Vitaceae

2.5.2 Sample Collection

Most of the plant species used in this study were collected from Lincoln University campus farms such as: Iverson Fields, Ashley Dene, Lincoln University Research Dairy Farm (LURDF), Horticultural Research Area (HRA) and the campus wineries (Figure 1). A few plant species, however, were collected from

Plant and Food Research farms in Lincoln, Canterbury. Most of the vegetables were accessed from the Biological Husbandry Unit (BHU), Lincoln in Canterbury.

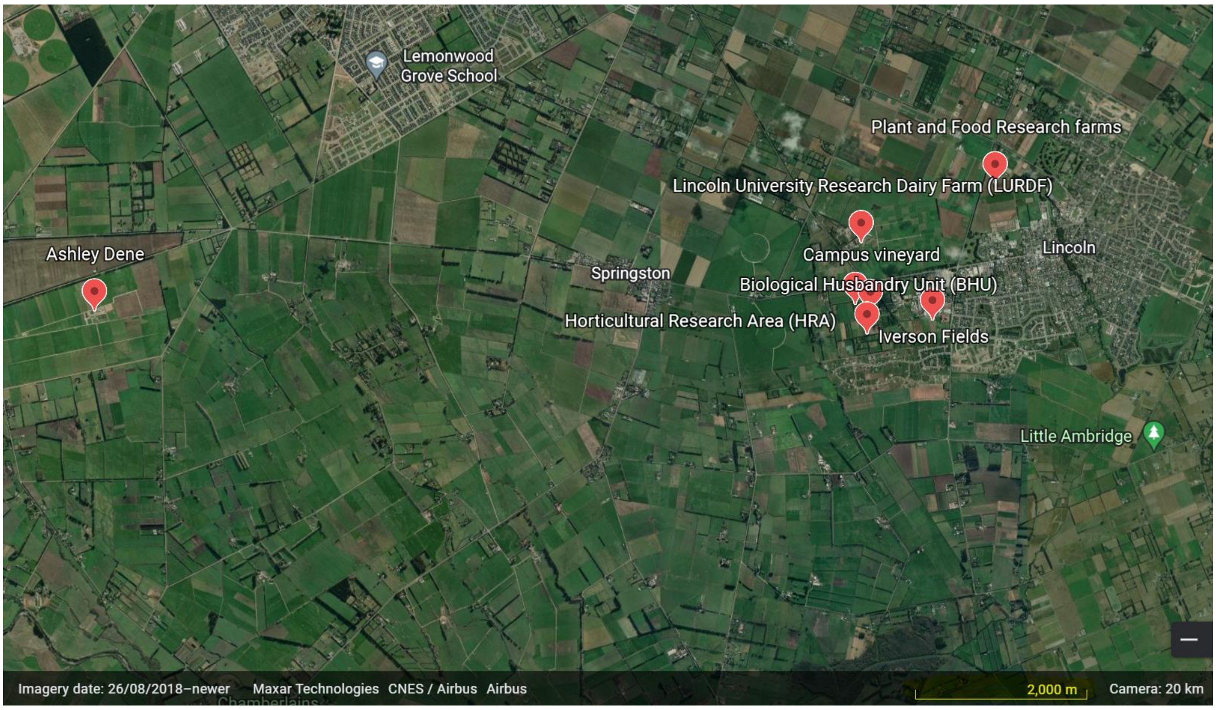


Figure 1: Location map of farms from which samples were collected for Chapter 2. Scale of the map is highlighted in yellow in the bottom right corner of the map. (Source: Google Earth).

I followed the methods of Wyse et al. (2016) and Padulles Cubino et al. (2018), and collected 70 cm long, sun-exposed terminal shoots of the different tree and shrub species, but the lower 70 cm of the plant for herbs or grasses, as the lower parts of these plants are more susceptible to fire. For species that had a height <70 cm, I collected the whole plant as a sample. Samples were collected and tested between mid-March and mid-April 2021, as these months are part of the fire season in Canterbury (FENZ, 2020), and also coincide with the drier stages of many summer crops (i.e., when fuel of crops is likely to be driest). The maximum temperatures for the month of March and April 2021 at Lincoln were 28˚C and 29.7˚C respectively, while the total rainfall (mm) was 7.4mm and 36.8mm respectively (FAR, 2021).

2.5.3 Flammability Variable Measurements

Methods for flammability measurements described by Jaureguiberry et al. (2011), later adapted by Wyse et al. (2016) and Padulles Cubino et al. (2018) were used in this study, wherein the samples were tested on a version of the apparatus used by Wyse et al. (2016; Figure 2). I burnt 8 samples per species (with an exception to a couple of species that were considered two varieties, so I collected 8 samples per variety) resulting in 392 flammability tests. All the samples were air-dried for 24 hours in a lab at room temperature (20˚C) in order to match the sample moisture content to the ignition source (Wyse et al., 2016; Wyse et al., 2018). All samples were air dried at the Field Research Centre (FRC) at Lincoln University

To conduct flammability tests, each sample was placed horizontally on the grill of the device and preheated for two minutes by the burners situated below the grill. The burners were maintained to ensure that the grill temperature was at 150˚C during the burning period. This was done to simulate preheating of fuel that occurs, wherein the flames are approaching the vegetation (Burger and Bond, 2015). A blowtorch was also positioned beneath the grill to act as the ignition source for the samples. Prior to preheating the samples, the weight of each sample was obtained by using a handheld hanging scale and a visual estimation of the percentage of dead material was also recorded. During the two minutes of preheating, the length (cm), width (cm) and height (cm) of the samples were recorded.

Once the samples were preheated for two minutes, the blowtorch was switched on for 10 seconds to attempt to ignite the samples. The time to ignition was recorded to the nearest second if the sample ignited within 10 seconds. Time to ignition ranged between 0 and 9.5 s which was rescaled by subtracting it from 10 to derive an ignition score by giving higher values to those species that ignited faster and lower values to those species that took the longest to ignite. The remaining measurements took place as soon as the blowtorch was turned off, which included: burning time, maximum temperature and burnt biomass. Burn time was measured using a stopwatch and the time was recorded from the moment the blow torch was turned off until the sample had no more flames on it. Maximum temperature was measured using a digital infrared thermometer (Fluke 572; Fluke Corp., Everett, WA, USA) by pointing it toward the flames on the burning sample. Burnt biomass was measured by visually estimating the amount of original biomass burned. These estimations were done by two people to reduce observer error (Wyse et al., 2016). These flammability variables were measured to describe flammability of plants at the shoot-level (Wyse et al., 2018; Padulles Cubino et al., 2018). I checked the Fire and Emergency NZ website prior to every burn day, ensuring that the local fire danger on the day was not high. Additionally, I checked that the wind speed was not higher than 20km/hr. On days that the weather failed to meet these safety regulations, I had to postpone the burn to a later day.

Figure 2: Device used to burn plants to measure flammability (Source: Tanmayi Pagadala).

2.5.4 Functional Trait Measurements

Prior to air drying samples, a subsample which represented each sample was weighed to obtain the fresh mass (FM). These subsamples were re-weighed after 24 hours at room temperature and were then placed in trays into dry ovens (at 60˚C) for 48 hours before measuring the subsamples again to obtain the dry mass (DM) measurement. The moisture content (MC) of the sample on a dry mass basis of the sub-samples at the time of burning was calculated using the following equation:

MC = [(FM – DM)/DM] x 100

The length, width and height of the samples were also measured on the day of burns to calculate the volume of the sample, which was later used to calculate the bulk density:

Bulk Density = Dry Mass/Volume

2.5.5 Statistical Analysis

All statistical analyses were conducted using R version 4.1.0 (R Development Core Team 2013), and Genstat 19th edition. Analysis of variance (ANOVA) was performed using Genstat to compare flammability differences between different plant groups and between the species followed by a Tukey post-hoc test to examine significant differences between means. Additionally, to test the effects of functional traits (bulk density, moisture content and, dead material (%) on the likelihood of ignition, generalized linear models were run with binomial distribution and a logit link function on Genstat.

A Principal Component Analysis (PCA) was performed using the "PCA"function from "FactoMiner" package (Lê et al. 2008) to examine the patterns in flammability across species using burn time, maximum temperature, burnt biomass and ignition score per sample and visualized the outcomes using "factoextra" package (Kassambara and Mundt 2020). Due to the variables being measured in different units, the PCA was performed on centred and standardised data. K-means clustering (Hartigan and Wong 1979) was used to divide the species into flammability categories following Fogarty (2001) and Wyse et al. (2016): Very High, High, Moderately High, Moderate, Moderately Low, and Low, with an additional Very Low category for many species tested in this study. A correlation matrix was plotted with all the flammability traits and functional traits using "GGally" (Schloerke et al. 2021) and "tidyverse" (Wickham et al. 2019) packages.

2.6 Results

2.6.1 Differences in flammability between groups and taxa

The 47 species I tested showed wide variation in their flammability traits (Figure 2). In a PCA on all four flammability traits (Figure 3), almost all variation in flammability was explained by the first PCA axis (93.3%), suggesting that flammability is a one-dimensional variable for the plant species in my study. All flammability variables were positively loaded on PCA axis 1 (IS = 0.964, MT = 0.966, BT = 0.954, BB = 0.979). The second PCA axis explained only 3.2% of the variation in the data, and was weakly negatively associated with BB, MT and, IS (loadings = -0.034, -0.055, -0.198, respectively) and positively correlated with BT (loading = 0.291). Consequently, PC1 scores were used as an index of overall flammability in subsequent analyses. Species that had a higher score on the first axis were higher in flammability. Species from the fruits category were the highest in flammability whereas the species from grazing herbs, vegetables, weeds, and pasture grasses were the lowest in flammability (Figure 3).

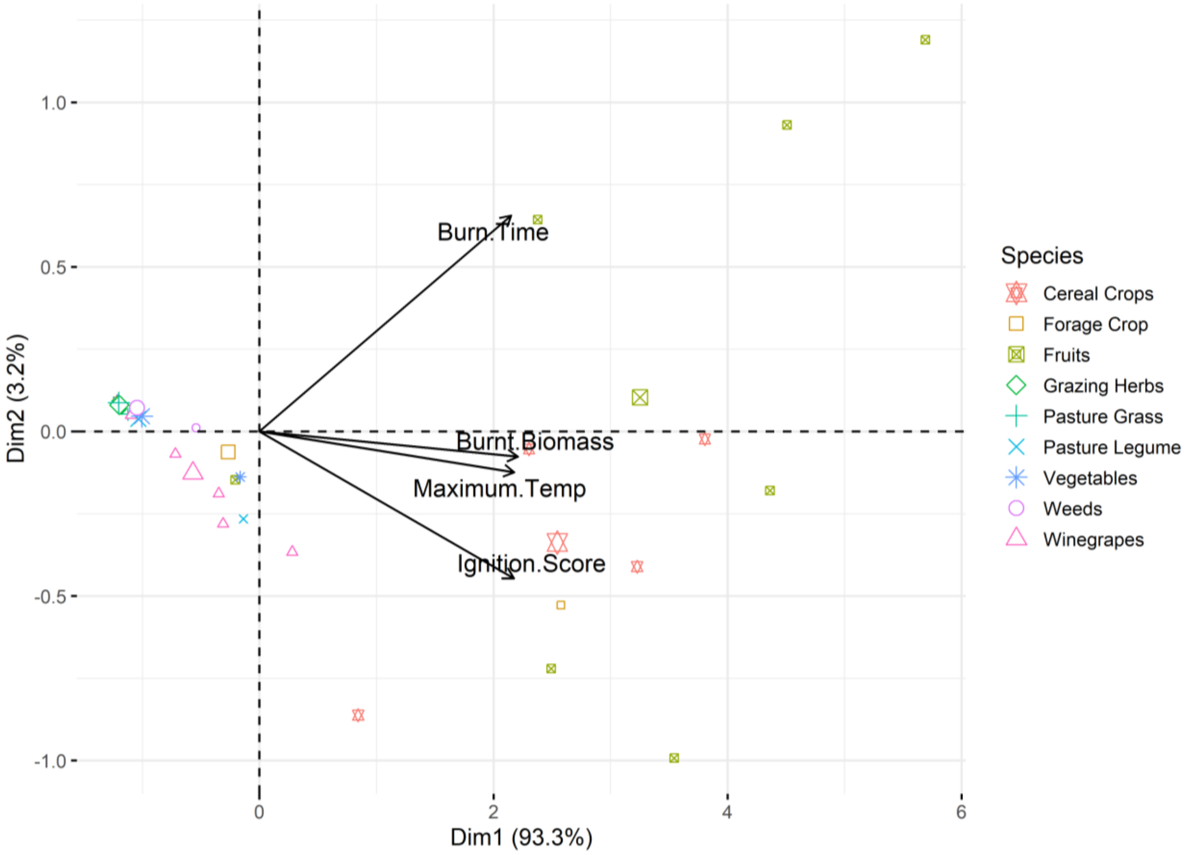


Figure 3: Principal components analysis (PCA) of the four flammability traits (burn time, maximum temperature, burnt biomass and ignition score). Points indicate species that belong to different plant groups, as indicated by the legend on the right side of the graph. The first two ordination axes explained 93.3% and 3.2% of the variation in the data, respectively. See Table 1 for the different species used in this study. Larger symbols for each plant group represent the centroid for that group.

There were significant differences in flammability between the 47 taxa and between the nine plant groups for flammability variables and functional traits (Tables 2 & 3; Figures 4 & 6). Fruit crops and cereal crops were the two most flammable groups, while forage crops, grazing herbs, pasture grasses, pasture legumes, vegetables, weeds and, winegrapes all had low flammability (Figure 4).

Table 2: Statistical differences between 9 Plant Groups (cereal crops, forage crops, fruits, grazing herbs, pasture grasses, pasture legumes, vegetables, weeds, winegrapes) including PCA loading scores of different flammability variables and functional traits.

Y-variable	DF	F-score	p-value	PC1 scores
Bulk Density	8, 375	21.86	<.001	0.030
Burning Time	8, 375	38.42	<.001	-0.472
Burnt Biomass	8, 375	62.12	<.001	-0.486
Max Temp	8, 375	88.83	<.001	-0.481
Dead Material	8, 375	15.84	<.001	-0.159
Ignition Score	8, 375	83.06	<.001	-0.484
Moisture Content	8, 375	24.36	<.001	0.221

Table 3: Statistical differences between the 47 crop and pasture taxa including PCA loading scores of different flammability variables and functional traits.

Y-variable	DF	F-score	p-value	PC1 scores
Bulk Density	46, 337	9.58	<.001	0.030
Burning Time	46, 337	15.86	<.001	-0.472
Burnt Biomass	46, 337	22.29	<.001	-0.486
Max Temp	46, 337	27.7	<.001	-0.481
Dead Material	46, 337	13.47	<.001	-0.159
Ignition Score	46, 337	50.66	<.001	-0.484
Moisture Content	46, 337	18.12	<.001	0.221

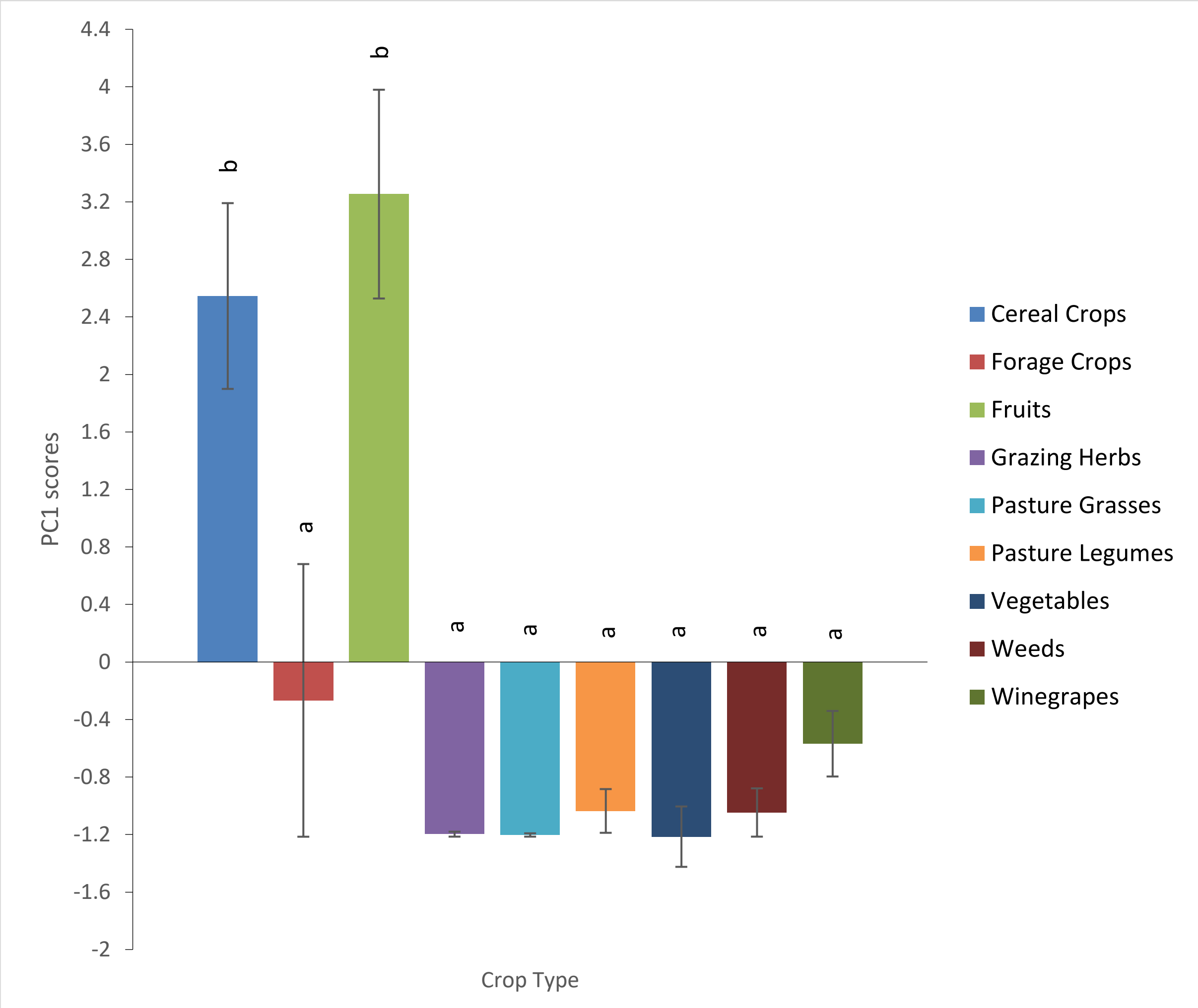


Figure 4: Bar graph showing the scores of the different plant groups determined by the first axis of a principal component analysis (PCA) with their standard errors (cereal crops = ±0.646, forage crops = ±0.948, fruits = ±0.726, grazing herbs = ±0.017, pasture grasses = ±0.012, pasture legumes = ±0.152, vegetables = ±0.210, weeds = ±0.168, winegrapes = ±0.228). The letters 'a' and 'b' represent the Tukey's test of significance (multiple pair-wise comparisons) shown on top of each bar.

Species PC1 scores were used to rank the flammability of each species and then group species into seven flammability categories using k-means clustering (Figure 5). *Pyrus communis* (pear) was the most flammable species tested, and the only one placed in the Very High Flammability category. The two apple varieties (*Malus domestica* – Braeburn and Royal Gala) were next most flammable, placed in the High category. *Triticum aestivum* (wheat), *Rubus idaeus* (raspberries), and *Avena fatua* (oats) were categorised as Moderate-High. Species in the Low Flammability category included *Securigera varia* (hairy canary), *Cucurbita* spp. (squash), *Ribes uva-crispa* (gooseberries), three wine grape varieties (*Vitis vinifera* – Merlot, Sauvignon Blanc and, Chardonnay) and a weed, *Chenopodium album* (fathen). Finally, most of the species tested (28) were in the Very Low category, and most of these (all but four: *Trifolium pratense* (Red Clover), *Vitis vinifera* (Reisling variety), *Phalaris aquatica* (Phalaris) and

Plantago lanceolata (Plantain)) were so low in flammability that all samples failed to sustain a flame on our device after the blowtorch was turned off after 10 seconds (Figure 5).

While the k-means clustering of the PC1 scores allowed us to assign species to different flammability categories, ANOVA on each flammability variable revealed some important nuances in interspecific comparisons of flammability. Pears (*Pyrus communis*) were found to be significantly different to many other taxa in most flammability variables (Figure 6). However, apple Braeburn (*Malus domestica.* Braeburn), apple Royal Gala (*Malus domestica*. Royal Gala), wheat (*Triticum aestivum*) and, oats (*Avena fatua*) had similarly high flammability as pears, for several flammability variables, except burning time, when only Braeburn apples were not significantly different from pears. However, when maximum temperatures were considered, pears, both apple varieties, Barnea olives (*Olea europaea. Barnea*), Blueberries (*Vaccinium spp.*) and Raspberries (*Rubus idaeus*) all had the highest values (Figure 6d).

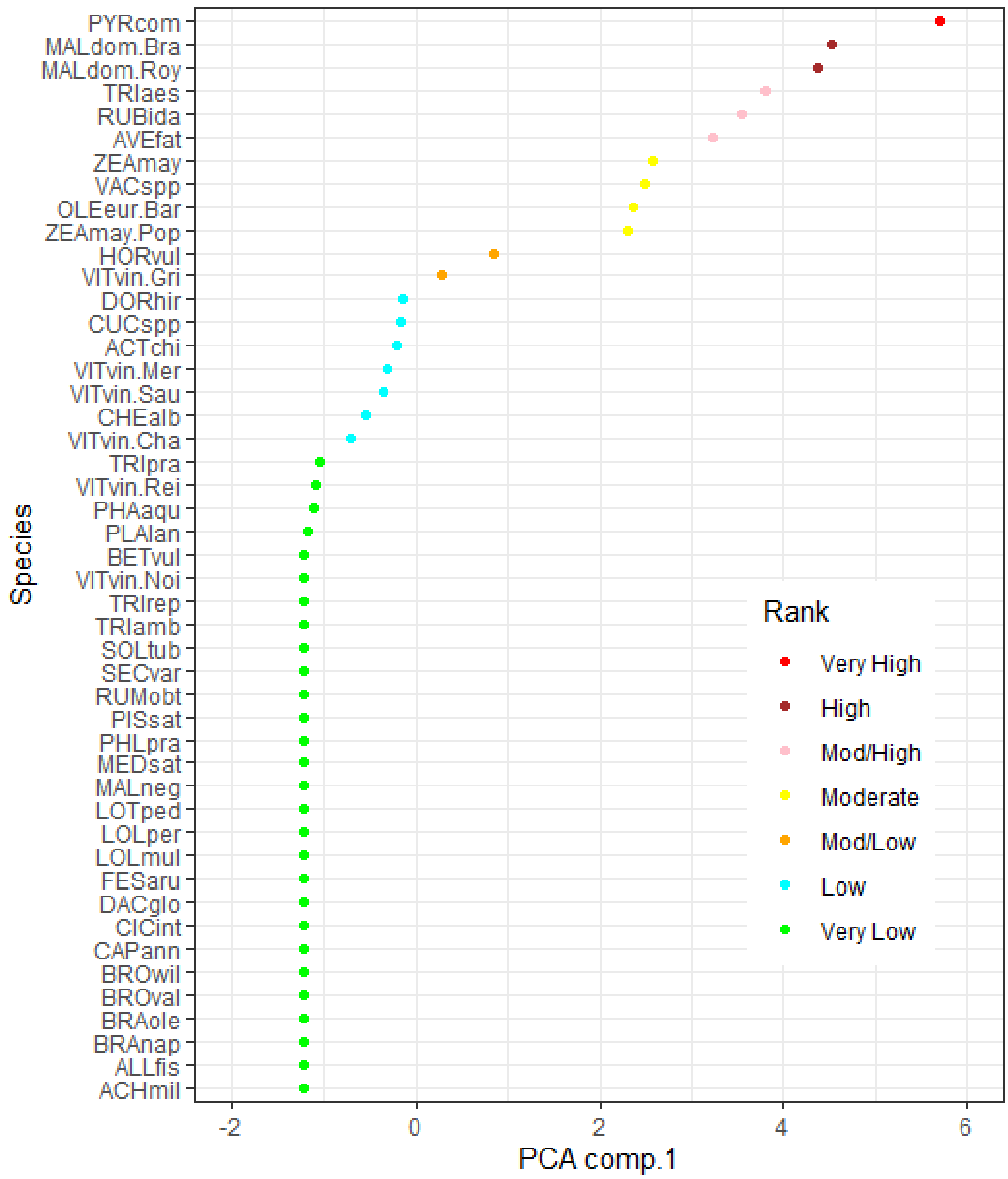
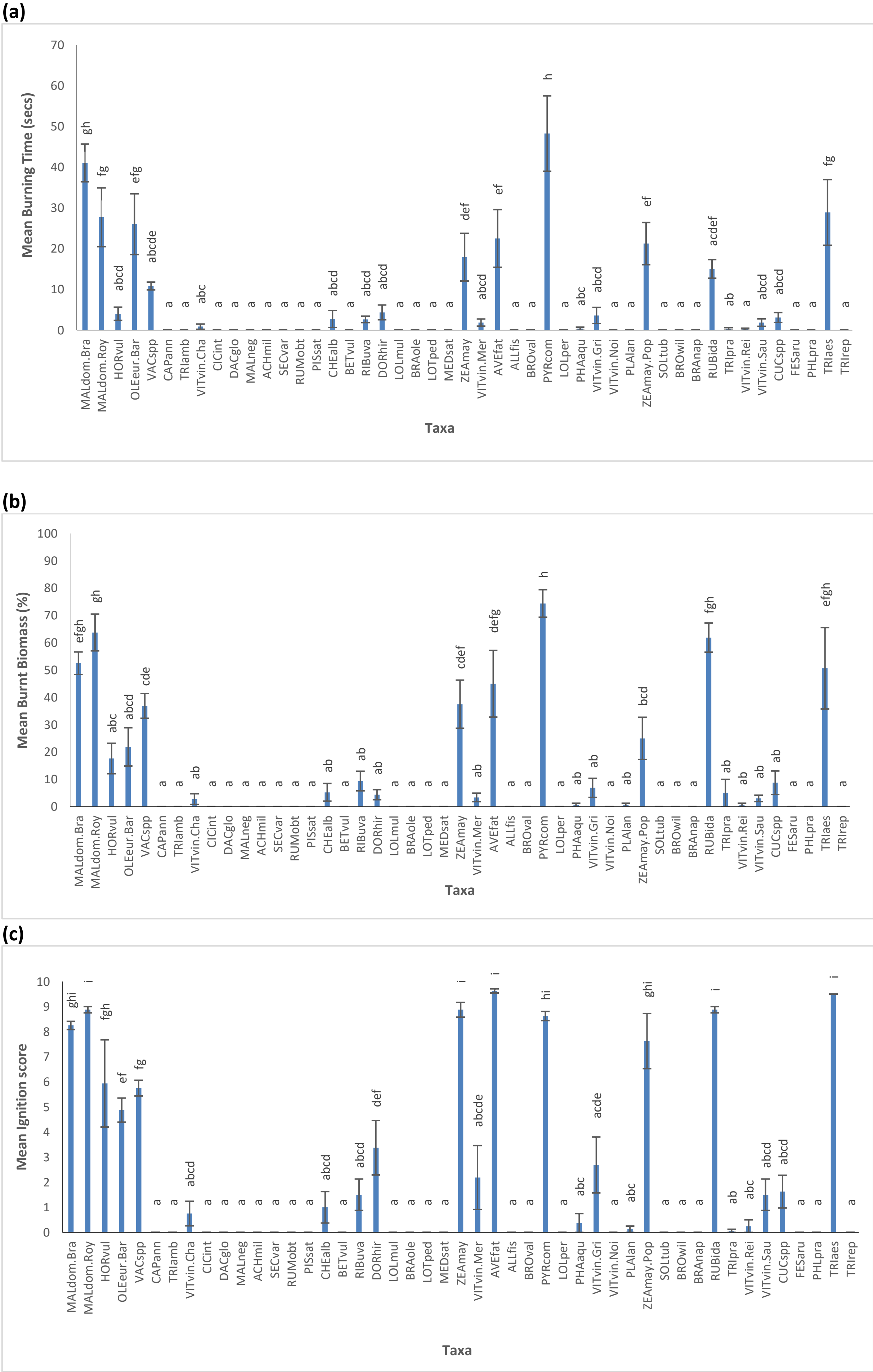


Figure 5: Flammability rankings for the study taxa determined by the first axis of a principal component analysis (PCA). The PCA was computed using the flammability variables maximum temperature, burn time, burnt biomass and ignition score. The first PCA axis was positively correlated with the four flammability variables and explained 93.3% of the variation in the data. Flammability categories were determined using k-means clustering. See Table 1 for definition of species codes.


(a)
Mean Burning Time (secs)
Taxa
(b)
Mean Burnt Biomass (%)
Taxa
(c)
Mean Ignition score
Taxa
MALdom.Bra
MALdom.Roy
HORvul
OLEeur.Bar
VACspp
CAPann
TRIamb
VITvin.Cha
CICint
DACglo
MALneg
ACHmil
SECvar
RUMobt
PISsat
CHEalb
BETvul
RIBuva
DORhir
LOLmul
BRAole
LOTped
MEDsat
ZEAmay
VITvin.Mer
AVEfat
ALLfis
BROval
PYRcom
LOLper
PHAaqu
VITvin.Gri
VITvin.Noi
PLAlan
ZEAmay.Pop
SOLtub
BROwil
BRAnap
RUBida
TRIpra
VITvin.Rei
VITvin.Sau
CUCspp
FESaru
PHLpra
TRIaes
TRIrep

(d)

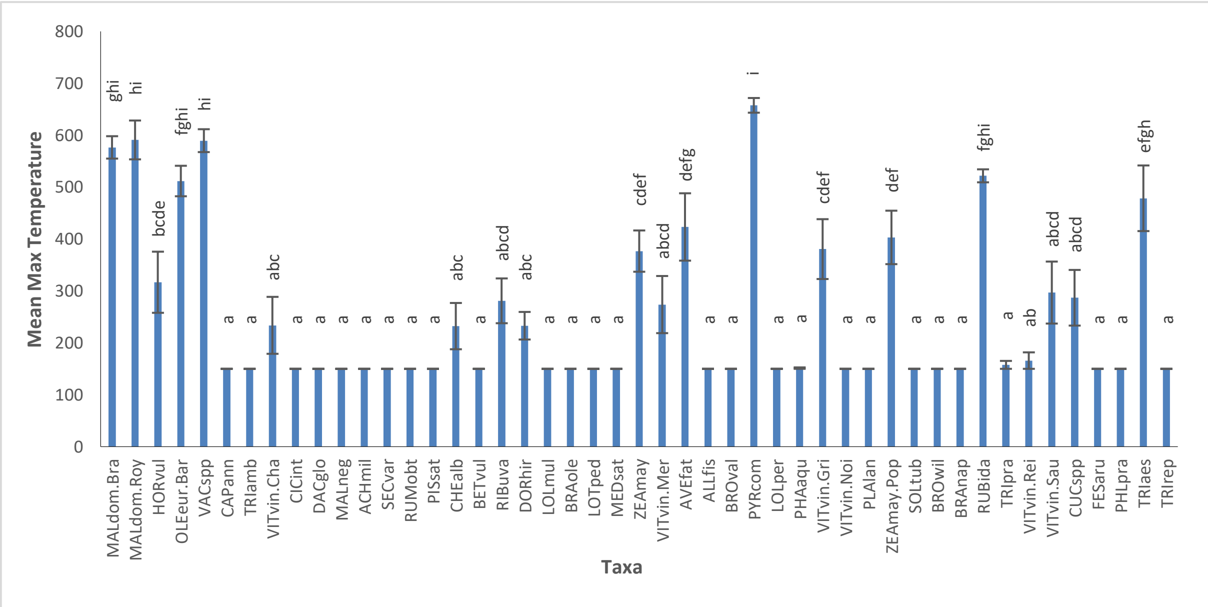


Figure 6: Bar graphs showing the means of the different flammability variables for each of the 47 species tested along with their Tukey's test of significance (multiple pair-wise comparisons) as indicated by the different letters shown on top of each bar. From the top: (a) mean burning time (seconds), (b) mean burnt biomass, (c) mean ignition score and (d) mean maximum temperature. See Table 1 for definition of species codes.

2.6.2 Traits associated with flammability

In a principal components analysis (PCA) on both the flammability variables and functional traits measured (Figure 7), 56.6% of the variation was explained by the first PCA axis, while only 17.1% of the variation was explained by the second PCA axis. IS, MT, BT, BB, and DM were negatively loaded (loadings = -0.484, -0.481, -0.472, -0.486, -0.159, respectively) while MC and BD were positively loaded on PCA axis 1 (loadings = 0.221, 0.030, respectively). On PCA axis 2, MT, BT, BB, and MC were negatively loaded (loadings = -0.144, -0.119, -0.078, -0.470, respectively) and IS, DM, and BD were positively loaded (loadings = 0.011, 0.477, 0.715, respectively).

The traits that were most associated with flammability were MC and DM, wherein MC was negatively correlated, and DM was positively correlated (Figure 7). For example, species with very high MC and very low DM such as fodder beet (code = BETvul) and onion (code = ALLfis) (Figure 8b, c) were also amongst those that did not ignite (Figure 6c). Some cereal crops such as oats (code = AVEfat) and wheat (code = TRIaes) had high DM (Figure 8b) and were amongst the species that ignited the most (Figure 6c). One exception for taxa that had high DM but didn't ignite as often was fathen (Figure 8b). The mean BD for the species plantain (*Plantago lanceolata*) was significantly different from all taxa apart from barley (*Hordeum vulgare*).

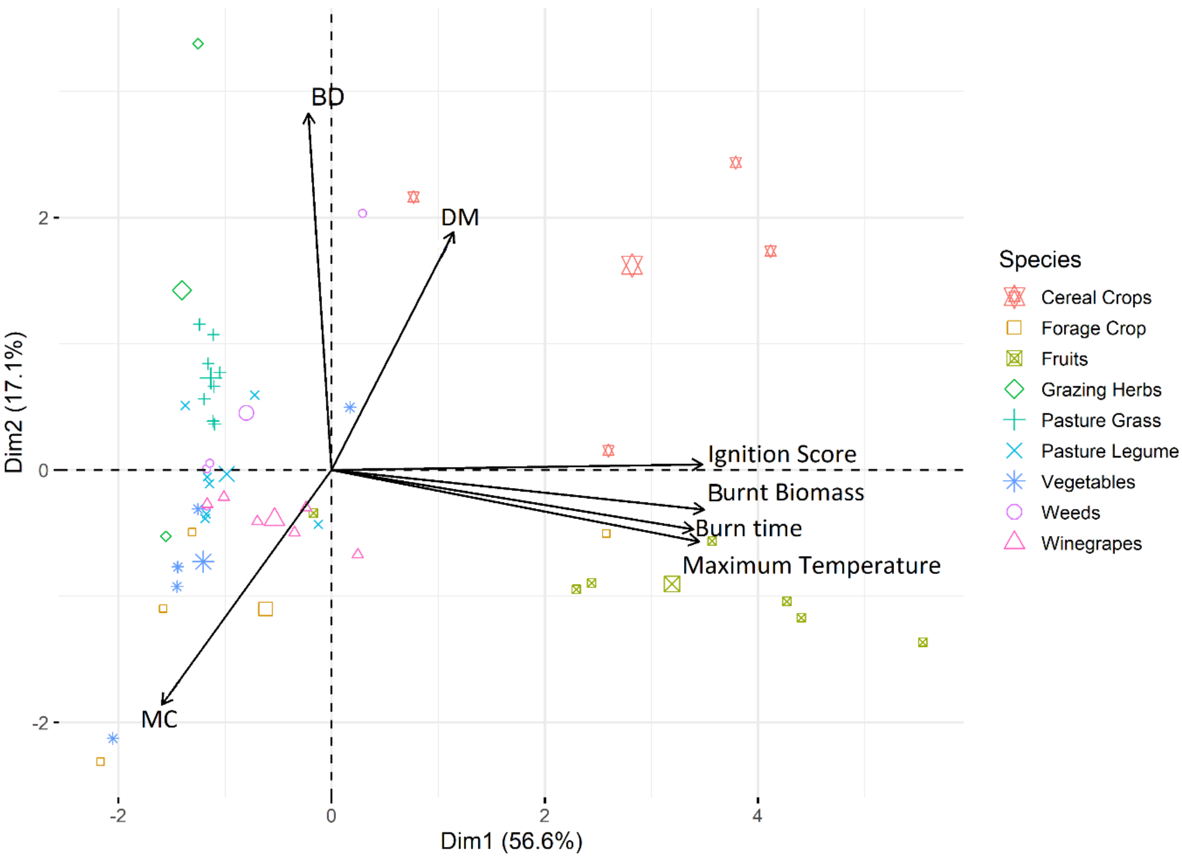
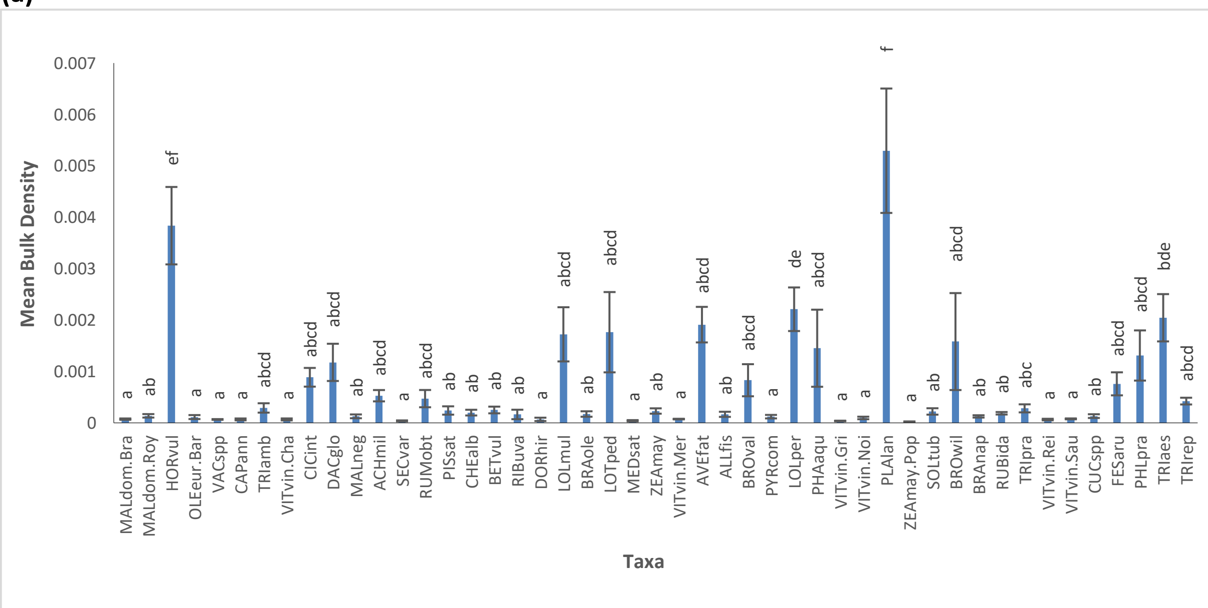
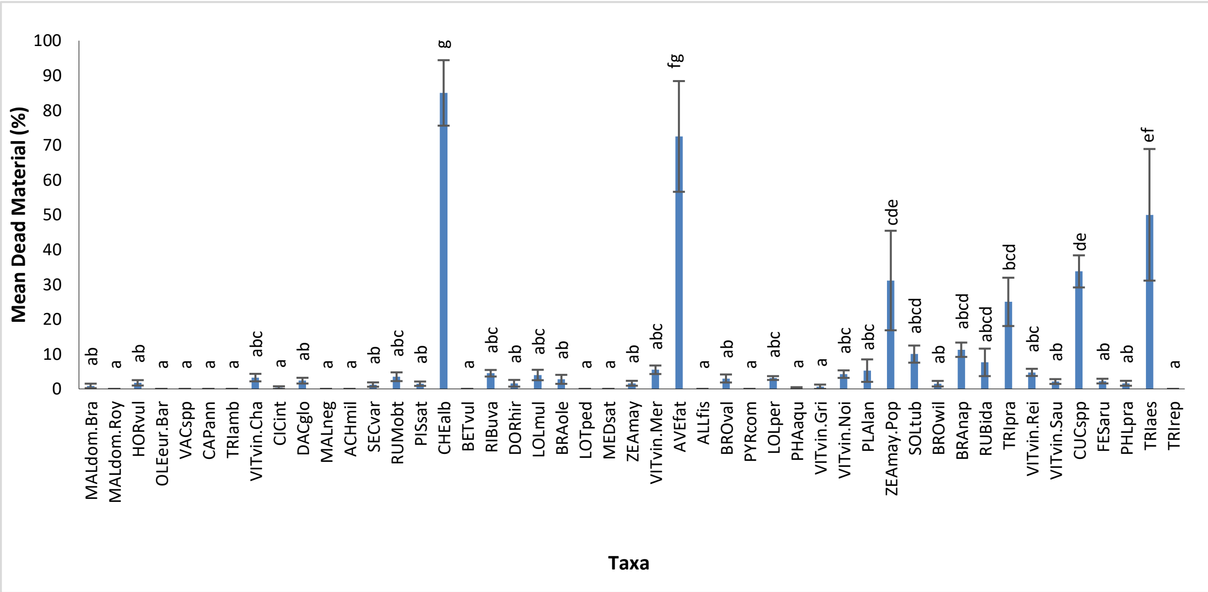


Figure 7: Principal components analysis (PCA) of all the measured variables (burn time, maximum temperature, burnt biomass, ignition score, moisture content (MC), bulk density (BD), and dead material percentage (DM)). Points indicate species that belong to different plant groups, as indicated by the legend on the right side of the graph. The first two ordination axes explained 56.6% and 17.1% of the variation in the data, respectively. See Table 1 for the different species used in this study. Larger symbols for each plant group represent the centroid for that group.

(a)



(b)



(c)

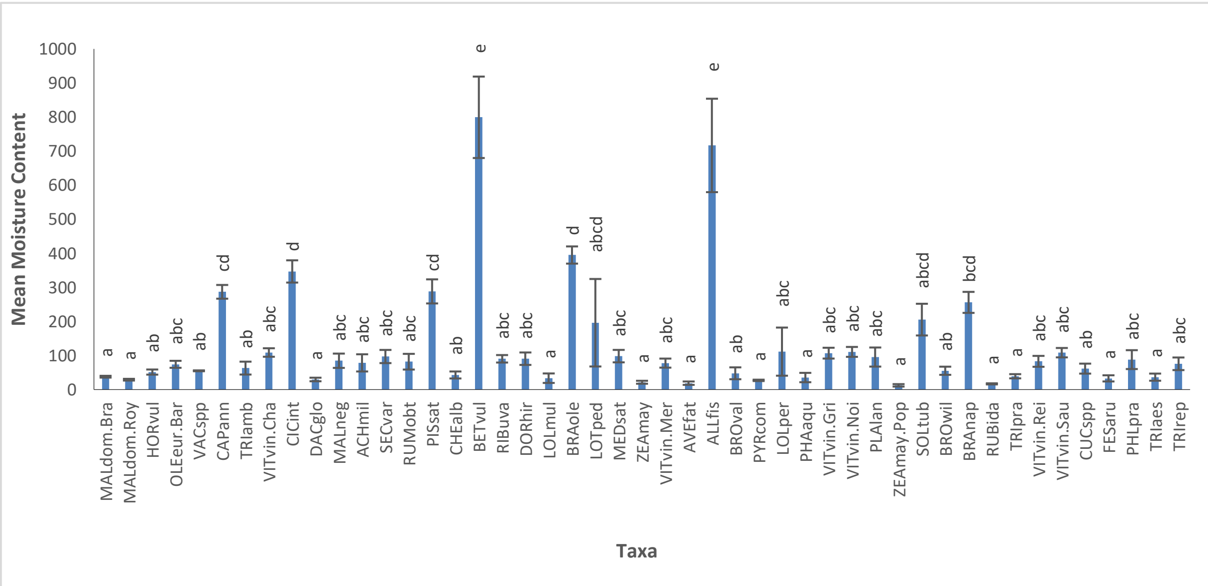


Figure 8: Bar graphs showing the means of the different functional traits for each of the 47 species tested along with their Tukey's test of significance (multiple pair-wise comparisons) as indicated by the different letters shown on top of each bar. From the top: (a) mean bulk density), (b) mean dead material, (c) mean moisture content. See Table 1 for definition of species codes.

The correlation matrix showed that most functional fuel traits (MC and DM) were significantly correlated with the flammability traits (IS, MT, BT and BB) except bulk density (BD) (Figure 9). All flammability variables had significant positive correlation with each other and with dead material and had significant negative correlation with moisture content whereas only maximum temperature had significant negative correlation with bulk density (Figure 9).

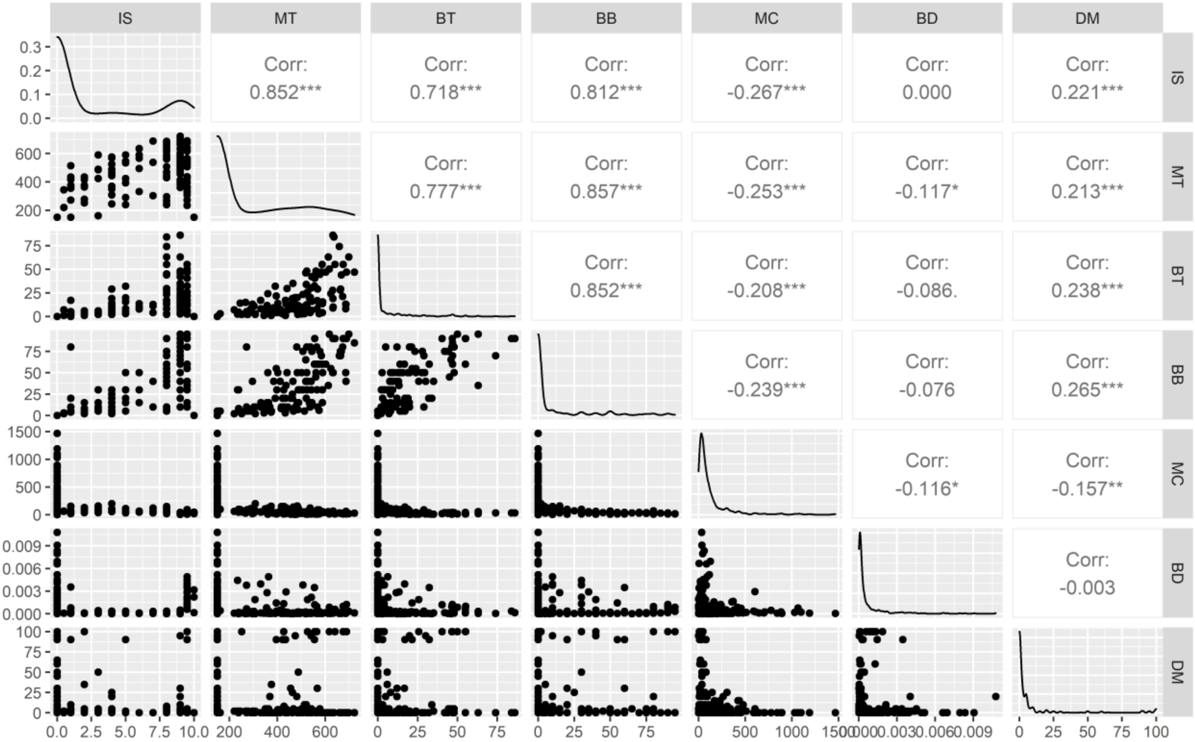


Figure 9: Correlation matrix visualising the Pearson's correlation coefficient between the flammability traits (IS = ignition score, MT = maximum temperature, BT = burn time, BB = burnt biomass) and functional fuel traits (MC = moisture content, BD = bulk density, DM = dead material). Statistically significant correlations are marked by an asterisk. *,,*** Significant at *P* ≤ .05, 0.1 and 0.001, respectively.**

My data showed that over half of my samples did not ignite, so I sought to investigate which traits might influence the likelihood of ignition. To test this, generalized linear models were run with a binomial distribution. Both moisture content (*X*=40.45; DF=1,382; P<0.001) and dead material (*X*=8.29; DF=1,382; P= 0.004) were significantly related to whether a sample ignited or not, with high moisture content and low dead material associated with non-ignitions. Bulk density was not significantly related to sample ignition (*X*=2.82; DF=1,382; P=0.093).

2.7 Discussion

The primary aim of this chapter was to quantify the shoot-level flammability of common crop, pasture and weed species that occur on Canterbury farms. I sampled 47 taxa in 9 different plant groups (see Table 1) across the Lincoln University and Plant and Food Research farms in Canterbury, New Zealand. These taxa varied greatly in their flammability, though most were rated Low or Very Low in flammability. Furthermore, 24 of the 47 taxa failed to sustain a fire on our device once the ignition source was turned off. This suggests that crop and pasture species are excellent choices for green firebreaks and will be successful in mitigating wildfires, given their failure in sustaining a fire. The traits that were most associated with flammability were moisture content and dead material, wherein a high moisture content resulted in low flammability, while a high percentage of dead material resulted in comparatively higher flammability.

2.7.1 Patterns in plant flammability between groups and taxa

There was considerable variation in the flammability characteristics of the 47 taxa of common crop, pasture and weed species. For example, the recorded ignition time of the samples ranged from 0.5 s to 9.5 s with 0 s for no ignition, the maximum temperature varied between 150 ˚C - 722 ˚C, burn time varied between 0 s – 86 s, and burnt biomass varied between 0 % - 95 %. However, only a small number of taxa were considered to have High or Very High Flammability (Common Pear (*Pyrus communis*) and Apples (*Malus domestica* var. *Braeburn*, *M. domestica* var. *Royal Gala*)). The common pear (*Pyrus communis*) had high values for all flammability variables measured (e.g.: a mean maximum temperature of 657.5˚C). In terms of plant groups, fruit crops and cereal crops had high flammability, while vegetable crops, grazing herbs, pasture grasses, pasture legumes and weeds were very low in flammability.

Moreover, the most flammable species in this study were from the Rosaceae (*Pyrus communis, Malus domestica* var. *Braeburn*, *M. domestica* var. *Royal Gala*, *Rubus idaeus*) and Poaceae (*Triticum aestivum*, *Avena fatua*) families. Shoot flammability is known to be phylogenetically conserved, i.e., close relatives are likely to have similar flammability, though there are some differences within taxonomic groups (Cui et al. 2020b). Samples of *Pyrus communis (var. 'Louise Bonne of Jersey')* and *Malus domestica* collected in NZ have previously been identified as being highly flammable (Cui et al. 2020b), further supporting our findings. Similarly, other grass species, such as *Ammophila arenaria, Bromus hordeaceus* and *Festuca novae-zelandiae* were also found to have high flammability (Cui et al., 2020b).

The findings from this study support existing evidence that some members of the Poaceae are highly flammable. There are several studies that have found that Poaceae species are highly flammable, some of which are *Pennisetum ciliare* (Brooks et al., 2004), *Bromus hordeaceus, Ammophila arenaria, Chionochloa macra, Chionochloa rigida, Poa cita* and others from Cui et al.'s (2020b) study, *Triodia* spp. (Prior et al., 2017) and other invasive grasses (Cornwall, 2022). On the contrary, species such as *Dactylis glomerata, Bromus valdivianus* and other pasture grasses that were tested in this study have also been found to have low flammability, despite belonging to the Poaceae family. This indicates that flammability can vary widely even within the same family, but especially within Poaceae, a family of more than 11,000 species and several life history strategies (Linder et al., 2018). Grass flammability is also known to be influenced by evolutionary history (Simpson et al., 2016). The wide variation in flammability among species, taxonomic families and plant groups highlights the relevance of investigating the flammability of a variety of species grown in agricultural fields and farm areas in order to comprehend how species flammability might result in variation in the effects of fire on those landscapes worldwide.

2.7.2 Functional traits associated with flammability

The flammability of the species is affected by plant traits such as moisture content, dead material, and bulk density. A recent study found that moisture content was the most commonly reported flammability trait and was found to be directly related to flammability components (Popović et al., 2021). It is generally agreed that the amount of moisture present in living plant material has a significant impact on the rate at which fire spreads and the flammability of the material (Peacock, 1980). Vegetables, forage crops, and legumes, which have high moisture content, were all found to have very low flammability wherein most samples did not even ignite during burning. This finding is in line with a mounting body of literature that demonstrates a strong negative relationship between the flammability of a plant and its moisture content (Ganteaume et al., 2012; Murray et al., 2013; Grootemaat et al., 2017).

Species with a high percentage of dead materials retained on the plant are often associated with high flammability, due to the inherently low moisture content of dead fuel, and lower energy required to achieve combustion (Bond and Van Wilgen, 2012). However, in my study, some flammable species (pears, apples) were amongst the taxa with a low percentage of dead material, and, one species, the weed, fathen (*Chenopodium album),* had the highest dead material percentage amongst the taxa in my study but was classified under the Low Flammability category. This finding is probably due to its taxonomy; *Chenopodium* spp. are noted for their high salt content and recognised as having low flammability in other parts of the world (Myers et al., 2005).

Ignitability (measured as Ignition Score) was strongly correlated with the maximum temperature at which my samples burned. However, over half of my samples did not ignite, and high moisture content and low percentage of dead material were associated with these non-ignitions. For example, *Beta vulgaris 'Mangelwurzel'* (fodder beet) and *Allium fistulosum* (onion) had high moisture contents compared to other taxa and also had 0% dead material and hence did not ignite. We can therefore conclude that the plant traits such as moisture content and dead material can be used to describe the differences in flammability as well as to determine species flammability.

2.7.3 Guidelines for fire management in agricultural landscapes

The effectiveness of green firebreaks is largely reliant on the selection of suitable plant species, i.e., those with low flammability. This indicates that they are able to withstand fire, although this does not guarantee that they are fire proof. Low-flammability plant species do not readily ignite and will slow down and possibly stop the progression of fires if they are present (Cui et al., 2019). However, if conditions are extremely dry and fires are hot enough with favourable winds, then any living material will burn (i.e. no plant is fire proof).

While there has been some investigation of the comparative flammability of crop or pasture plants (Baxter and Woosaree, 2013; Xaud et al. 2009), to date there has been no widespread screening of the flammability of a wide range of crops, pastures and other plants found on agricultural lands. Such work is vital to enable the reconfiguration of agricultural landscapes to control fire (Kelly et al. 2020). In this chapter, I have demonstrated that there was a wide range of flammability among crop, pasture and weed taxa sampled from Canterbury farms. More than half of the species tested were of very low flammability, suggesting that there is great potential for using crop and pasture species as part of green firebreaks to reduce fire spread. Fruit crops were most flammable, followed by cereals and some fruit-bearing shrubs (e.g. raspberries and blueberries).

So, which species should we plant to prevent fire spread in cropping landscapes? Given that most of the species tested in this study were of very low flammability, possibly all the species that are categorized as either Low or Very Low flammability may be used as part of green firebreaks on cropping landscapes (Table 4).

Table 4: A list of crop and pasture species that could potentially be used as green firebreaks on farms stating their family, flammability category (according to Fogarty (2001)) and, ignition (yes – at least sample ignited during testing, no – no samples ignited during testing)

Common Name	Species	Family	Flammability category	Ignition (Yes/No)
Hairy Canary	*Dorycnium hirsutum*	Fabaceae	Low	Yes
Squash	*Cucurbita* spp. (*maxima, moschata, pepo*)	Cucurbitaceae	Low	Yes
Gooseberries	*Ribes uva-crispa*	Grossulariaceae	Low	Yes
Merlot	*Vitis vinifera. Merlot*	Vitaceae	Low	Yes
Sauvignon Blanc	*Vitis vinifera. Sauvignon Blanc*	Vitaceae	Low	Yes
Fathen	*Chenopodium album*	Amaranthaceae	Low	Yes
Chardonnay	*Vitis vinifera. Chardonnay*	Vitaceae	Low	Yes
Red Clover	*Trifolium pratense*	Fabaceae	Very Low	Yes
Riesling	*Vitis vinifera. Riesling*	Vitaceae	Very Low	Yes
Phalaris	*Phalaris aquatica*	Poaceae	Very Low	Yes
Plantain	*Plantago lanceolata*	Plantaginaceae	Very Low	No
Fodder Beet	*Beta vulgaris 'Mangelwurzel'*	Amaranthaceae	Very Low	No
Pinot Noir	*Vitis vinifera. Pinot Noir*	Vitaceae	Very Low	No
White Clover	*Trifolium repens*	Fabaceae	Very Low	No
Caucasian Clover	*Trifolium ambiguum*	Fabaceae	Very Low	No
Potatoes	*Solanum tuberosum*	Solanaceae	Very Low	No
Coronilla	*Securigera varia*	Fabaceae	Very Low	No
Dock	*Rumex obtusifolius*	Polygonaceae	Very Low	No

Dwarf Snow Pea	*Pisum sativum*	Fabaceae	Very Low	No
Timothy	*Phleum pratense*	Poaceae	Very Low	No
Lucerne	*Medicago sativa*	Fabaceae	Very Low	No
Common Mallow	*Malva neglecta*	Malvaceae	Very Low	No
Lotus	*Lotus pedunculatus*	Fabaceae	Very Low	No
Perennial Ryegrass	*Lolium perenne*	Poaceae	Very Low	No
Italian Ryegrass	*Lolium multiflorum*	Poaceae	Very Low	No
Tall Fescue	*Festuca arundinacea*	Poaceae	Very Low	No
Cocksfoot	*Dactylis glomerata*	Poaceae	Very Low	No
Chicory	*Cichorium intybus*	Asteraceae	Very Low	No
Californian Bell Pepper	*Capsicum annum*	Solanaceae	Very Low	No
Prairie Grass	*Bromus willdenowii*	Poaceae	Very Low	No
Pasture Brome	*Bromus valdivianus*	Poaceae	Very Low	No
Kale	*Brassica oleracea var. sabellica*	Brassicaceae	Very Low	No
Rape Crop	*Brassica napus*	Brassicaceae	Very Low	No
Onion	*Allium fistulosum*	Amaryllidaceae	Very Low	No
Common Yarrow	*Achillea millefolium*	Asteraceae	Very Low	No

Agricultural fields in areas with high fire risks can serve as firebreaks, limiting the spread of fire and the overall area burned (Loepfe et al., 2012). In this study, I examined the flammability of 47 species from agricultural areas. While few species had high flammability, comparatively more species had low flammability, highlighting the possibility of selecting suitable low flammability species to create a fire-wise agricultural landscape. Not only has this study identified species suitable for green firebreaks, given that they are agricultural species, it suggests that planting low-flammability species can be deployed as part of a profitable and diverse agricultural business in Canterbury.

However, care should be taken when considering growing certain fruit trees and shrubs (apple, pear, raspberry, blueberry) in fire-prone landscapes as these were highly flammable and can pose a serious fire hazard. On the other hand, vegetable crops, pasture grasses, and pasture legumes that have been identified as low to very low flammability can be used as green firebreaks wherever they are appropriate to grow. Suggestions on how such crops could be planted across a farm are provided in Chapter 4.

Chapter 3

Identifying low flammable species in New Zealand agricultural landscapes

3.1 Introduction

In Chapter 2, I compared the flammability of a wide range of crop and pasture species commonly planted in Canterbury. However, crop and pasture species are not the only plant species found in agricultural landscapes, and these other plant species can contribute greatly to the overall flammability of a farm. In NZ, there is considerable native vegetation found in agricultural landscapes, with 25% of native vegetation in the country occurring on sheep and beef farms (Pannell et al., 2021). While public conservation land supports the majority of remaining native vegetation present in NZ (61.5%), sheep and beef farms are the second highest (24.5%), followed by 'other' types of land use such as lifestyle blocks and grazing lots (9.6% combined), forestry (2.8%), dairy (1.4%), horticulture, arable and urban (<0.1% each) (Pannell et al., 2021). Considering the substantial amount of native vegetation present on agricultural land, to properly assess the likely contribution of crop and pasture species to either suppressing or promoting fires on farms, it is necessary to compare the flammability of crop and pasture species with that of native species.

3.2 Plant flammability research in New Zealand

NZ is one of the better-studied countries in the world in terms of knowledge of plant flammability, with previous research having measured the flammability of at least 269 species (Table 5). For example, Wyse et al. (2016) measured shoot flammability of 50 NZ indigenous and 10 exotic species across 37 families, and samples were collected from across a wide range of habitats in both the North and South Islands of NZ. These 60 species varied greatly in their flammability, with the invasive shrub gorse (*Ulex europaeus*) being the most flammable, along with Manna Gum (*Eucalyptus viminalis*), Kūmarahou (*Pomaderris kumeraho*), Rimu (*Dacrydium cupressinum*) and Silver Beech (*Lophozonia menziesii*), while many of the lowest flammability species were native trees such as Karamū (*Coprosma robusta*) Karaka (*Corynocarpus laevigatus*), Kohekohe (*Dysoxylum spectabile*), Hangehange (*Geniostoma ligustrifolium*) and Five-finger (*Pseudopanax arboreus*). Padullés Cubino et al. (2018) measured the morphological traits and whole plant- and shoot-level flammability of 51 native and exotic plant species commonly found in tussock grasslands of the south-eastern South Island in NZ and found that invasive forbs, such as *Crepis capillaris*, *Pilosella officinarum*, *Pilosella piloselloides* and *Hypochaeris radicata*, have reduced community-level flammability of 25 years of invasion by reducing fuel loads, fuel continuity, and flammability of the constituent species. Another study by Alam et al. (2020) used existing flammability data from Mason et al. (2016), Wyse et al. (2016) and Padullés Cubino et al. (2018) to analyse leaf- and shoot-level flammability of 43 common indigenous perennial NZ plants and found differences in flammability rankings at leaf-level and shoot-level. Moreover, a study by Cui et al. (2020b) measured shoot flammability of 120 NZ indigenous and 74 exotic species from the Tracheophyta (vascular plants) group which occur across a wide range of habitats around NZ and found the following: phylogenetic relatedness and plant shoot flammability are strongly associated; species from fire-prone habitats were more likely to have higher flammability than those from non-fire-prone habitats; and, lastly, that flammability varies within and among growth forms. Another study by Cui et al. (2020a) explored evolutionary patterns in shoot flammability across the *Dracophyllum* genus by measuring the shoot-level flammability of 21 *Dracophyllum* species and found that flammability can vary widely at the genus level.

Collectively, these studies demonstrate that the flammability of plant species found in NZ is highly variable, ranging from highly flammable endemic grasses and invasive trees and shrubs to low flammable rosette forbs and weeds, and native trees and shrubs (Wyse et al., 2016; Padullés Cubino et al., 2018; Alam, 2019; Alam et al., 2020; Cui et al., 2020a; Cui et al., 2020b). Furthermore, these studies show that both native and introduced plant species in New Zealand can be high or low in flammability; the country of origin does not necessarily result in a consistent level of flammability. These previous studies have identified a range of native tree species, such as Karamū (*Coprosma robusta*), Broadleaf (*Griselinia littoralis*), and Five-finger (*Pseudopanax arboreus*), which have low flammability and are found in Canterbury (Wyse et al., 2016). These species could be good candidates for planting in green firebreaks. Equally, as shown in Chapter 2, many common crop species found in Canterbury could also be used to establish green firebreaks. While these studies have provided valuable information, the question remains, how flammable are the crops and pastures of Canterbury farms relative to other plant species that occur in such landscapes?

Table 5: Studies that were used to compile the expanded data set of 269 species for Chapter 3.

Study Title	Authors	Year	Journal
A quantitative assessment of shoot flammability for 60 tree and shrub species supports rankings based on expert opinion. DOI: https://doi.org/10.1071/WF15047	Sarah V. Wyse, George L. W. Perry, Dean M. O'Connell, Phillip S. Holland, Monique J. Wright, Catherine L. Hosted, Samuel L. Whitelock, Ian J. Geary,	2016	International Journal of Wildland Fire

	Ke´vin J. L. Maurin and Timothy J. Curran.		
Community-level flammability declines over 25 years of plant invasion in grasslands. DOI: https://doi.org/10.1111/1365-2745.12933	Josep Padullés Cubino, Hannah L. Buckley, Nicola J. Day, Robin Pieper, Timothy J. Curran.	2018	Journal of Ecology
Plant functional traits associated with shoot flammability - PhD thesis, Lincoln University, New Zealand.	Md Azharul Alam	2019	Lincoln University Research Database
Shoot flammability is decoupled from leaf flammability but controlled by leaf functional traits. DOI: https://doi.org/10.1111/1365-2745.13289	Md Azharul Alam, Sarah V. Wyse, Hannah L. Buckley, George L. W. Perry, Jon J. Sullivan, Norman W. H. Mason, Rowan Buxton, Sarah J. Richardson, and Timothy J. Curran.	2019	Journal of Ecology
Shoot flammability of vascular plants is phylogenetically conserved and related to habitat fire-proneness and growth form. DOI: https://doi.org/10.1038/s41477-020-0635-1	Xinglei Cui, Adrian M. Paterson, Sarah V. Wyse, Md Azharul Alam, Kévin J. L. Maurin, Robin Pieper, Josep Padullés Cubino, Dean M. O'Connell, Djessie Donkers, Julien Bréda, Hannah L. Buckley, George L. W. Perry and Timothy J. Curran.	2020	Nature Plants
Shoot-level flammability across the *Dracophyllum* (Ericaceae) phylogeny: evidence for flammability being an emergent property in a land with little fire. DOI: https://doi.org/10.1111/nph.16651	Xinglei Cui, Adrian M. Paterson, Md Azharul Alam, Sarah V. Wyse, Kate Marshall, George L. W. Perry, Timothy J. Curran	2020	New Phytologist

3.2.1 Research aims

To compare the flammability of crop and pasture taxa to other species assessed for NZ, and specifically to determine whether the 47 crop and pasture taxa studied in Chapter 2 retain their flammability categories when compared to a wider group of plant species in NZ.

3.3 Methods

3.3.1 Species used in this study

To identify and compare low flammability species in NZ agricultural landscapes, I compiled existing shoot flammability data for an additional 269 NZ plant species across 82 families on top of the 47 taxa that were tested in Chapter 2 of this thesis; a total of 316 species. Species used for this chapter consist of both indigenous and exotic species. A list of the different sources and studies that were used to compile the data used for this chapter is included in Table 5 above.

It is to be noted that the shoot-level flammability tests are the same for all sources of data and follow the same protocol as those described in Chapter 2.

3.3.2 Data Analysis

A principal component analysis (PCA) was conducted, including four shoot-level flammability variables (burn time, burnt biomass, maximum temperature, ignition frequency; Figure 10). Ignition frequency was used here instead of ignition score due to the missing ignition time data for some species and was calculated as the percentage of samples of each species ignited during burning. This PCA allowed me to examine the differences in flammability between the plant species that occur on rural Canterbury farms and other plant species in New Zealand. The PCA was conducted in R version 4.1.0 (R Development Core Team 2014) using the “PCA”function from “FactoMiner” package (Lê et al. 2008) to examine patterns in flammability across species. K-means clustering was used to divide the species into flammability categories following Fogarty (2001) and Wyse et al. (2016): Very High, High, Moderately High, Moderate, Moderately Low, and Low, with an additional Very Low category for many species tested in this study.

3.4 Results

The first PCA axis (Dim1; Figure 10) explained 75.6% of the variation in the data and was positively associated with all four flammability variables (loadings = burn time: 0.432, burnt biomass: 0.512, maximum temperature: 0.553, ignition frequency: 0.496). The second PCA axis (Dim2; Figure 10) explained 14.3% of the variation in the data and was weakly negatively associated with three of the flammability variables (loadings = burnt biomass: -0.095, maximum temperature: -0.129, ignition frequency: -0.501) apart from burn time (loadings = 0.851), which was strongly positively associated with this axis.

Compared to the other plant species tested in NZ, crops and plants identified in rural Canterbury scored lower in all the measured flammability variables (Figure 10). Almost all crop and pasture species had a lower ignition frequency than many other plant species tested around NZ.

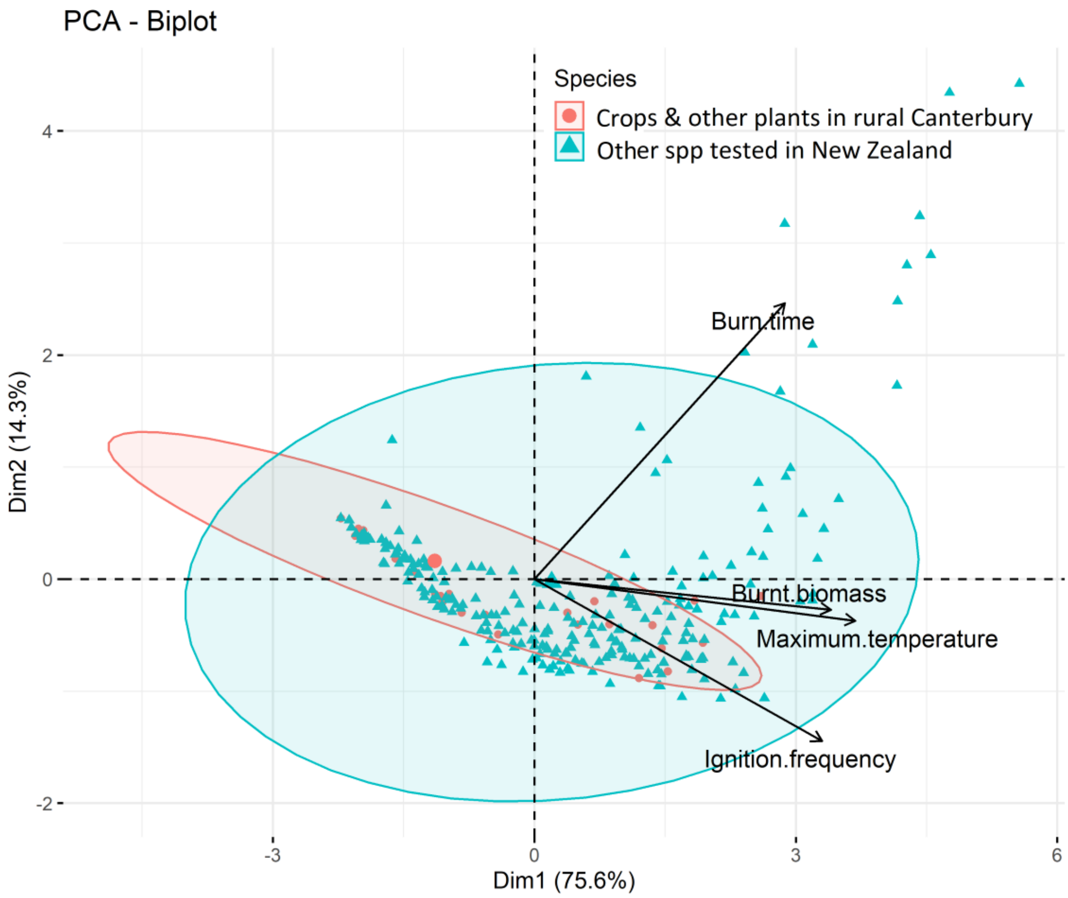


Figure 10: Principal components analysis (PCA) of the four measured flammability traits (burn time, maximum temperature, burnt biomass and ignition frequency). Points indicate species that belong to different plant groups, as indicated by the legend on the right side of the graph. The first two ordination axes explained 75.6% and 14.3% of the variation in the data, respectively. The two larger symbols for each species type represents the centroid for that group. See Appendix A for the different species used in this study.

Another finding to note is that the majority of the species (42 taxa) tested in Chapter 2 retained their flammability rankings in the expanded data set (Table 6). This was particularly the case with species categorised as either Low or Very Low in flammability, where only one species (Pasture Brome (*Bromus valdivianus)*) changed its flammability class (shifting from Very Low to Low, due to additional data on this species in the expanded dataset). The main exceptions to this were species designated as Very High or High in flammability in the Chapter 2 analysis, such as *Pyrus communis*, *Malus domestica* var. *Braeburn* and *M. domestica* var. *Royal Gala* (Table 6). This lack of change in flammability categorization in Chapter 2 suggests that these findings are robust, especially for species designated as Low or Very Low Flammability.

Table 6: Flammability rankings of the 47 crop and pasture species from Canterbury tested in Chapter 2 compared to their flammability rankings when included in the expanded data set of 269 other plants species in New Zealand.

Species	**Common Name**	**Flammability Category from Chapter 2**	**Flammability Category from Expanded Data Set**
Pyrus communis	Pears	Very High	High
Malus domestica. Braeburn	Apple Braeburn	High	Moderately High
Malus domestica. Royal Gala	Apple Royal Gala	High	Moderately High
Triticum aestivum	Wheat	Moderately High	Moderately High
Rubus idaeus	Raspberries	Moderately High	Moderately High
Avena fatua	Oats	Moderately High	Moderate
Zea mays	Maize	Moderate	Moderate
Vaccinium spp.	Blueberries	Moderate	Moderate
Olea europaea Barnea	Barnea Olives	Moderate	Moderate
Zea may. Popcorn	Popcorn Maize	Moderate	Moderate
Hordeum vulgare	Barley	Moderately Low	Moderately Low
Vitis vinifera. Pinot Gris	Pinot Gris	Moderately Low	Moderately Low
Dorycnium hirsutum	Hairy Canary	Low	Low
Cucurbita spp. (maxima, moschata, pepo)	Squash	Low	Low
Ribes uva-crispa	Gooseberries	Low	Low
Vitis vinifera. Merlot	Merlot	Low	Low
Vitis vinifera. Sauvignon Blanc	Sauvignon Blanc	Low	Low
Chenopodium album	Fathen	Low	Low
Vitis vinifera. Chardonnay	Chardonnay	Low	Low
Trifolium pratense	Red Clover	Very Low	Very Low
Vitis vinifera. Reisling	Reisling	Very Low	Very Low
Phalaris aquatica	Phalaris	Very Low	Very Low
Plantago lanceolata	Plantain	Very Low	Very Low
Beta vulgaris 'Mangelwurzel'	Fodder Beet	Very Low	Very Low
Capsicum annum	Californian Bell Pepper	Very Low	Very Low
Trifolium ambiguum	Caucasian Clover	Very Low	Very Low
Cichorium intybus	Chicory	Very Low	Very Low
Dactylis glomerata	Cocksfoot	Very Low	Very Low

Malva neglecta	Common Mallow	Very Low	Very Low
Achillea millefolium	Common Yarrow	Very Low	Very Low
Securigera varia	Coronilla	Very Low	Very Low
Rumex obtusifolius	Dock	Very Low	Very Low
Pisum sativum	Dwarf Snow Pea	Very Low	Very Low
Lolium multiflorum	Italian Ryegrass	Very Low	Very Low
Brassica oleracea var. sabellica	Kale	Very Low	Very Low
Lotus pedunculatus	Lotus	Very Low	Very Low
Medicago sativa	Lucerne	Very Low	Very Low
Allium fistulosum	Onion	Very Low	Very Low
Bromus valdivianus	Pasture Brome	Very Low	Low
Lolium perenne	Perennial Ryegrass	Very Low	Very Low
Vitis vinifera. Pinot Noir	Pinot Noir	Very Low	Very Low
Solanum tuberosum	Potatoes	Very Low	Very Low
Bromus willdenowii	Prairie Grass	Very Low	Very Low
Brassica napus	Rape Crop	Very Low	Very Low
Festuca arundinacea	Tall Fescue	Very Low	Very Low
Phleum pratense	Timothy	Very Low	Very Low
Trifolium repens	White Clover	Very Low	Very Low

3.5 Discussion

The primary aim of this chapter was to compare the flammability ranking of crop and pasture taxa to other species assessed for NZ, and identify low flammability species that are usually found in agricultural landscapes in NZ. I compiled existing shoot flammability data for a total of 316 plant species, including 47 taxa from Chapter 2 of this thesis. Flammability varied widely across the various species tested so far in New Zealand (Wyse et al., 2016; Padullés Cubino et al., 2018; Alam, 2019; Alam et al., 2020; Cui et al., 2020a; Cui et al., 2020b). In this chapter, I have demonstrated that crop and pasture species are generally less flammable than other plant species tested in NZ (Figure 10). Other plant species in NZ scored higher in all flammability variables than crop and pasture species. Moreover, the flammability rankings of the 47 crop and pasture species tested in Chapter 2 were slightly lower in rankings when added to the expanded data set of this chapter, or retained their rank as Low or Very Low Flammability, thus indicating that crop and pasture species are suitable candidates for planting as green firebreaks.

3.5.1 How does the flammability of common crops and pastures from Canterbury compare to that of other NZ species?

Overall, it is evidenced that the flammability of common crops and pastures from Canterbury is generally lower when compared to that of other NZ species. The flammability rankings of the 47 crop and pasture species tested in Chapter 2 were only slightly lower in rankings when compared to the expanded data set in this chapter (Table 6). The only differences in rankings were found for *Pyrus communis*, wherein the ranking decreased from Very High to High, for *Malus domestica. Braeburn* and *Malus domestica Royal Gala* wherein the ranking decreased from High to Moderately High, and lastly for oats *Avena fatua,* where the ranking decreased from Moderately High to Moderate. One species however, Pasture Brome (*Bromus valdivianus*), had an increase in its ranking from Very Low to Low. The rest of the 42 crop and pasture species retained their flammability rankings. This implies that the flammability categorization from Chapter 2 is very robust and solidifies the finding that crops and pastures typically found in Canterbury are of low flammability.

3.5.2 Low flammability species around New Zealand

From the 47 taxa tested in Chapter 2 of this thesis, 35 of the crop and pasture species had Low or Very Low flammability rankings, indicating that they could potentially be used as green firebreaks (see Table 4). However, three of these species (*Malva neglecta, Rumex obtusifolius* and *Chenopodium album*) are considered weeds on rural farms and hence should not be included in green firebreaks. While yarrow (*Achillea millefolium*) is also considered to be a weed in some circumstances (Bourdôt and Field, 1988; Johnston and Pickering, 2001), it is also a useful pasture around Canterbury. The rest of the low flammability species are from a range of different plant groups, such as forage crops, grazing herbs, pasture grasses, pasture legumes, vegetables and, winegrapes.

One of the studies from which existing flammability data was used as part of the expanded data set in this chapter was by Wyse et al., (2016). In this study, they found that lowland native forest species such as Karamū (*Coprosma robusta*), Karaka (*Corynocarpus laevigatus*), Five-finger (*Pseudopanax arboreus*), Broadleaf (*Griselinia littoralis*), Hangehange (*Geniostoma ligustrifolium*), Puriri (*Vitex lucens*), Kohekohe (*Dysoxylum spectabile*) and Kōtukutuku (*Fuchsia excorticata*) were of low flammability due to their high moisture contents (Wyse et al., 2016). They also noted that species such as Karamū have extensive environmental tolerances and are generally planted all around NZ, while species such as Karaka and Kohekohe are more suitable for milder climates. Another species found to have low flammability in that study was Lombardy Poplar (*Populus nigra*), which is a popular shelterbelt species on farms in NZ (Sturrock, 1973). Existing flammability data used from Padullés Cubino et al.'s (2018) study showed that native forbs such as *Brachyscome longiscapa, Lagenifera cuneta, Leptinella pectinate, Wahlenbergia albomarginata*, as well as other exotic forbs to be of low flammability.

From the data analysed thus far, it is evident that low flammability species are present across various plant groups in NZ including indigenous and native trees, shrubs, and forbs, exotic grasses, crop, and pasture species and even weeds. Apart from weeds and some invasive grasses, most of the other low flammability species from these groups may be appropriate to use as green firebreaks in NZ. I have supplied a table of the various low flammability species that can be used as green firebreaks in Chapter 4 (Table 7). Some native species such as Karamū (*Coprosma robusta*), Karaka (*Corynocarpus laevigatus*), Five-finger (*Pseudopanax arboreus*), Hangehange (*Geniostoma ligustrifolium*), Puriri (*Vitex lucens*), Kohekohe (*Dysoxylum spectabile*) and Kōtukutuku (*Fuchsia excorticata*) can be multi-purposeful as they can be used for green firebreaks as well as to promote biodiversity conservation and restoration. Native biodiversity is vital for the long-term viability and resilience of farm systems, for providing ecosystem services, and not just for conservation and cultural purposes (Maseyk et al., 2019). Given that New Zealand is experiencing a continued decline in native biodiversity (Ministry for the Environment and Stats NZ, 2022), implementing native tree and plant species into green firebreaks on farmland can contribute to improving the overall biodiversity status of NZ.

Moreover, using low flammability species such as Lombardy Poplar (*Populus nigra*) as green firebreaks have multiple benefits as it is also a common shelterbelt species in New Zealand. Likewise, using low flammability crop and pasture species mentioned in Chapter 2 of this thesis can also have multiple purposes as they can be used as green firebreaks, but could also provide food security to surrounding communities and help farmers and landowners to continue earning income while also reducing fire hazard, thereby contributing to NZ’s economy.

Chapter 4

General Discussion and Conclusions

4.1 Redesigning agricultural landscapes to reduce fire hazard

Around the world, changing fire regimes have caused significant changes to natural ecosystems and human-dominated landscapes. Hence, an understanding of how anthropogenic fire use alters with human demography, land-use patterns, and rising environmental restrictions is increasingly relevant for both fire and biodiversity management (Kelly et al., 2020). It is especially important to study the effects of fires in agricultural areas because they tend to have higher ignition sources (farm machinery, humans, wind, dry vegetation) than other landscapes (Catry et al., 2009; Ganteaume et al., 2013). However, there has been limited research that explores why fires are a problem in agricultural areas and their associated effects. Most research done on this topic is from European countries such as Spain, Portugal, France, and Italy (Moreira and Pe'er, 2018). There is a pressing need to investigate the flammability of agricultural landscapes, given that our landscapes are changing at alarming rates due to socioeconomic factors (Earl and Simmonds, 2018), which affect the frequency and intensity of fires.

The characteristics of fire regimes and their effects on biodiversity and human society are changing as a result of interactions between climate change, land use changes, and invasive species (Kelly et al., 2020). Habitats that were once largely fire-free are now increasingly at risk of damaging fires. One such landscape with increased fire danger are agricultural areas. Kelly et al., (2020) suggests that diversified agriculture can create a variety of habitats for plants and animals to enhance biodiversity, as well as mitigate fires. For example, agricultural and forestry practices in the Mediterranean basin that encourage mosaics of orchards, oak trees and low-flammability species were found to lower the likelihood of large, intense fires while still providing habitat for species-rich bird groups (Moreira and Pe’er, 2018). Similarly, more than 364,000 km of green firebreaks were planted in a variety of terrestrial ecosystems throughout China, which have the potential to increase biodiversity while decreasing fire activity in undesirable areas (Cui et al., 2019). However, there is very limited research identifying crop and pasture species that may be used as green firebreaks. Examples include pineapple crops (*Ananas comosus*) in Brazil (Xaud et al., 2009), Rocky Mountain fescue (*Festuca saximontana*), white clover (*Trifolium repens*) and yarrow (*Achillea millefolium*) pastures in Canada (Baxter and Woosaree, 2013) and Lucerne (*Medicago sativa*) pastures among pine plantations in New Zealand (Jolly and Guild, 1974), but these represent very few crops and pastures worldwide.

To address this knowledge gap, this thesis investigated the flammability of common pastures, crops and other plant species that occur on Canterbury farms, as well as identifying low flammability species that are typically found on agricultural landscapes in New Zealand.

4.2 Why are crops and pastures found on Canterbury farms low in flammability?

Most crop, pasture and weed species tested in my study were of low flammability, which indicates that crops and pastures could be used to reduce fire hazard on Canterbury farms. Specifically, forage crops, grazing herbs, pasture grasses, pasture legumes, vegetables and winegrapes were found to either be of low flammability or did not ignite at all, indicating that they may be useful to plant as green firebreaks.

One reason why some of these plant groups (especially vegetable crops and pasture grasses) were found to have low flammability or did not ignite is that they were grown under irrigation. From the species that I tested for flammability in Chapter 2, the crop and pasture species that are normally irrigated in Canterbury during their growing season are as follows: squash, gooseberries, plantain, fodder beet, white clover, potatoes, dwarf snow pea, timothy, perennial ryegrass, Italian ryegrass, chicory, Californian bell pepper, kale, rape crop, and onion. Most crops are irrigated in order to maintain a soil moisture reservoir for plant growth so that essential nutrients are transported throughout the crop (Walker, 1989). Being grown under high moisture conditions most of the time, means that irrigated crops have high moisture content and therefore are of low flammability. Species with high moisture content are often associated with delayed ignitions, slow rates of combustion and fire spread and sometimes may not ignite at all (Simpson et al., 2016), which reflects observations of the Low and Very Low flammability taxa tested in Chapter 2 of this thesis.

Another potential reason as to why pasture grasses, vegetable crops and other crop and pasture species are low in flammability relates to the traits which underpin a trade-off in flammability and palatability in plant species (Archibald et al. 2019; Gowda et al., 2022). Generally, the two main consumers of aboveground plant biomass are fires and herbivores, wherein the occurrence of one consumer affects the intensity and type of the other (Bond and Keeley, 2005; Archibald et al., 2019). Plants that are inedible or undesired by herbivores have certain life history traits or strategies that make them more flammable than palatable (Archibald et al., 2019). For instance, fires burn more readily through dry grasses due to their ease of ignition and ability to support a fire as a result of their high carbon (C) to nitrogen (N) ratio (Simpson et al., 2016). Also, chemical compounds such as tannins (a bitter polyphenol) present in some plant species not only deter herbivores (decreases palatability) (Cooper and Owen-Smith, 1985), but also decrease decomposition rates of the plant material (Kraus et al., 2003) and enabling dead fuel to be available for longer (increases flammability).

On the other hand, grazers favour plants that are low in carbon (C) to nitrogen (N) ratio and high in energy and protein as it is more digestible, have high phosphorous content and in general provide the animals with a well-rounded diet to support their metabolic processes (Owen-Smith and Cooper, 1989; Archibald et al., 2019). Plants with high moisture content are preferred by grazing animals as it decreases dependency on external water sources (Jarman, 1973). Also, large herbivores must ingest huge quantities of leaves to achieve their daily nutritional needs (Shipley, 2007). Hence, they prefer plants which can be eaten with large bites, have high biomass (high bulk density) distributed in space, and have few structural adaptations like spines (Shipley, 2007). Moreover, browsing can reduce the height and canopy volume of shrubs and small trees in habitats where the available plant species are primarily palatable, thereby creating a gap between fuel layers and preventing fires from spreading into the canopy (Endress et al., 2012; Foster et al., 2020).

These traits which make certain plant species more palatable to wild herbivores also make such species appetizing to livestock, and also to human consumers. Indeed, many varieties of such species have been selectively bred to enhance these palatability traits, thus also reducing their flammability. This means that many of the species prized for food by humans or livestock are likely to have the additional benefit of being low in flammability due to traits, such as high moisture content (Simpson et al., 2016), high bulk density (Shipley, 2007), high phosphorus content and low carbon to nitrogen ratio (Owen-Smith and Cooper, 1989). This trade-off between flammability and palatability is found not only in grasses in savanna ecosystems (Archibald et al., 2019; Hempson et al., 2019), but also in forest ecosystems (Gowda et al., 2022). A recent study based on Patagonian woody plants found that flammability and digestibility are negatively related in which highly digestible plants were likely to be less flammable than those with high fibre content, indicating that herbivory and fire spread may be influenced by differences in the source of energy consumed (Gowda et al., 2022). The fact that this trade-off is found in multiple ecosystems that are quite different in composition (i.e., both savannas and forests), suggests that this trade-off between palatability and flammability may be a more general relationship, though this remains to be tested.

4.3 Recommendations to farmers: species for green firebreaks on New Zealand farms

Climate change is expected to change the fire regimes, extend fire seasons, and increase fire occurrence in boreal and temperate regions around the globe, including New Zealand (Langer et al., 2021). This means that New Zealand will be faced with more severe wildfires in the future. Hence, it is crucial that property and farm owners, conservationists and fire researchers begin to implement a wider range of fire management strategies, including the use of green firebreaks.

From my findings in Chapter 2 of this thesis, and the overall analysis of low flammability species around New Zealand, I recommend that the following species can be used as part of green firebreaks on rural land and farms around New Zealand (Table 7). However, not all of the native species mentioned below are appropriate to plant in all parts of rural New Zealand. Some of these native species are naturally restricted to particular parts of New Zeland and should only be planted within their natural range.

Table 7: A list of low flammability plant species that are suitable for use as green firebreaks on rural land and farms around New Zealand.

Species	Scientific Name	Plant group
Lombardy poplar	*Populus nigra*	Exotic Trees
Fodder Beet	*Beta vulgaris 'Mangelwurzel'*	Forage Crop
Kale	*Brassica oleracea* var. *sabellica*	Forage Crop
Rapeseed	*Brassica napus*	Forage Crop
Gooseberries	*Ribes uva-crispa*	Fruit Crop
Plantain	*Plantago lanceolata*	Grazing Herb
Chicory	*Cichorium intybus*	Grazing Herb
Aromatic aniseed	*Anisotome aromatica*	Herb
Haast's carrot	*Anisotome haastii*	Herb
Creeping Everlasting Daisy	*Helichrysum filicaule*	Herb
Small-leaved Cranesbill	*Geranium microphyllum*	Herb
Creeping Eyebright	*Euphrasia dyeri*	Herb
Kawakawa	*Piper excelsum*	Native Shrub
Māpou (Red Matipo)	*Myrsine australis*	Native Shrub
Hūpiro	*Coprosma foetidissima*	Native Shrub
Mirror bush	*Coprosma repens/ C. serrulata*	Native Shrub
Poroporo	*Solanum laciniatum*	Native Shrub
Kaikōmako	*Pennantia corymbosa*	Native Shrub
Pittosporum divaricatum	*Pittosporum divaricatum*	Native Shrub
Weeping Matipo	*Myrsine divaricata*	Native Shrub
Low growing coprosma	*Coprosma cheesemanii*	Native Shrub
Coprosma crassifolia	*Coprosma crassifolia*	Native Shrub
Mingimingi	*Coprosma propinqua*	Native Shrub
Māhoe (whitey wood)	*Melicytus ramiflorus*	Native Shrub
Broadleaf	*Griselinia littoralis*	Native Trees
Hangehange	*Geniostoma ligustrifolium*	Native Trees
Five-finger	*Pseudopanax arboreus*	Native Trees

Karamū	*Coprosma robusta*	Native Trees
Kōtukutuku	*Fuchsia excorticata*	Native Trees
Lancewood	*Pseudopanax crassifolius*	Native Trees
Kōwhai	*Sophora microphylla*	Native Trees
Mānatu (Ribbonwood)	*Plagianthus regius*	Native Trees
Kohekohe	*Dysoxylum spectabile*	Native Trees
Putaputawētā (marbleleaf)	*Carpodetus serratus*	Native Trees
Māmāngi (tree coprosma)	*Coprosma arborea*	Native Trees
Karaka	*Corynocarpus laevigatus*	Native Trees
Phalaris	*Phalaris aquatica*	Pasture Grass
Italian Ryegrass	*Lolium multiflorum*	Pasture Grass
Pasture Brome	*Bromus valdivianus*	Pasture Grass
Perennial Ryegrass	*Lolium perenne*	Pasture Grass
Prairie Grass	*Bromus willdenowii*	Pasture Grass
Tall Fescue	*Festuca arundinacea*	Pasture Grass
Timothy	*Phleum pratense*	Pasture Grass
Cocksfoot	*Dactylis glomerata*	Pasture Grass
Red Clover	*Trifolium pratense*	Pasture Legume
Caucasian Clover	*Trifolium ambiguum*	Pasture Legume
Coronilla	*Securigera varia*	Pasture Legume
Lotus (big trefoil)	*Lotus pedunculatus*	Pasture Legume
Lucerne	*Medicago sativa*	Pasture Legume
White Clover	*Trifolium repens*	Pasture Legume
Hairy canary-clover	*Dorycnium hirsutum*	Pasture Legume
Squash	*Cucurbita spp. (maxima, moschata, pepo)*	Vegetable Crop
Californian Bell Pepper	*Capsicum annum*	Vegetable Crop
Dwarf Snow Pea	*Pisum sativum*	Vegetable Crop
Onion	*Allium fistulosum*	Vegetable Crop
Potatoes	*Solanum tuberosum*	Vegetable Crop
Supplejack	*Ripogonum scandens*	Vine
Pohuehue	*Muehlenbeckia australis*	Vine
Sauvignon Blanc	*Vitis vinifera.* Sauvignon Blanc	Winegrapes
Reisling	*Vitis vinifera.* Reisling	Winegrapes
Pinot Noir	*Vitis vinifera.* Pinot Noir	Winegrapes

Pinot Gris	*Vitis vinifera.* Pinot Gris	Winegrapes
Merlot	*Vitis vinifera.* Merlot	Winegrapes
Chardonnay	*Vitis vinifera.* Chardonnay	Winegrapes

4.4 Designing a farm landscape with low flammability species as firebreaks

The main objective of a firebreak is to keep a fire under control and stop it from spreading (Cui et al., 2019). Green firebreaks should therefore be deliberately positioned to use current fuel barriers like roads, rivers, lakes, and hills in order to segregate areas at risk of fire (Chen, 1994). Green firebreaks on ridges have been demonstrated to be effective in China in putting out fires since winds there tend to have greater friction (Cui et al., 2019). It is also advised that shrubs and trees be planted on both sides of ridgelines because the ecological circumstances there may be more challenging for plants (for example, drier, thinner soils, more exposed places) (Chen, 1994). Considering the abovementioned and, keeping in mind the objective of a firebreak, I have developed a demonstration of a potential fire-wise (i.e., low fire threat) agricultural landscape (Figure 11) in a mixed cropping farm scenario, such as may occur on the Canterbury Plains. It is to be noted that Figure 11 shows a general variety of crops and cropping location and is not restricted to any one season of a year. Furthermore, this planting approach is designed primarily from the point of view of fire mitigation, other factors (local environmental conditions, economics of crop returns, the desire for enhanced biodiversity outcomes) would all mean that this scheme would need to be amended accordingly. However, it is aimed primarily at showing what might be possible to using planting design to reduce fire hazard on Canterbury farms.

Firstly, the farm is bounded by strips of low flammability native tree species (also acting as shelterbelts) along with tracts of low flammability pasture grasses or legumes adjacent to the belt of trees. The western and northern strips of green firebreaks help in protecting the farm from prevailing nor'wester winds, which are typical in Canterbury (Jane, 1986) and eastern parts of South Island, New Zealand (Williams, 2009). The southern and eastern strips of firebreaks will protect fires coming from those directions, which are perhaps less likely, but will also protect neighbouring properties from a fire starting on the property in question. A similar mix of strips of low flammability native trees with adjacent tracts of pasture grasses or legumes are used to border the higher flammability commercial crops, fruit trees (orchards) and houses within the farm. Recent field experiments in Gabon, central Africa by Cardoso et al. (2018) found that the change in fire intensity between a grassy savannah and a rainforest patch is partly driven by the change in grass composition, with less flammable grasses closer to the forest. By incorporating tracts of low flammability pasture grasses or legumes adjacent to the belt of native trees, it is intended to mimic the similar change in fire behaviour (i.e., decrease in fire temperature and intensity) (Cardoso et al., 2018) for the landscape in Figure 11. Not only does this mix act as a 'buffer zone' by providing an extra layer of protection to the farm, crops, and houses, but these strips of lower flammability species can act as biodiversity corridors, amplifying the biodiversity values of the farm.

There is a higher risk of an intense fire if the fire reaches highly flammable crops. For example, wheat (*Triticum aestivum* L.) was amongst the most flammable crops tested in Chapter 2 of this thesis and hence poses a high fire threat. However, if this highly flammable crop is planted in the middle of a mosaic of low flammability crops (such as low flammability vegetable crops, forage crops, pasture grasses and legumes) in the inner paddocks of the farm, it will provide additional protection. Moreover, the higher flammability cereal/commercial crops are planted downwind from the main house that is located on the western edge of the farm to reduce fire threat to that house. Similarly, the highly flammable fruit trees/orchard are also positioned to be distant from houses and other infrastructure. Moreover, despite the high foliage flammability of fruit trees, the fire hazard in the orchard could be mitigated by judicious trimming of lower branches to separate ground and canopy fuels, where this is compatible with the production of such crops.

While the main aim of this landscape design is to reduce fire spread of any potential fires, it comes with additional benefits such as pollination, providing animal shelter from harsh winds (nor'wester and southerlies) and allows for crop rotation, which can be mediated by the flammability score/ranking of the crop. Having a mixture of native trees and other plant species will attract a range of different pollinators, improving both the biodiversity and production values of the farm (Maseyk et al., 2019). The main benefit of crop rotation is that it helps return nutrients to the soil without the need for synthetic inputs (such as fertilizers) which helps to maintain soil fertility, and also aids in pest, weed and disease control management (Ball et al., 2005; Tariq et al., 2019; Yu et al., 2022). Historically, Canterbury is known for its mixed cropping system wherein cash and cereal crops (arable cropping) are cultivated for 2-4 years and followed by clover-grass pastures (grazed pasture) for the next 2-4 years (Haynes and Francis, 1990). Arable crops and clover-grass pastures have distinct nutrient cycles and contrasting effects on soil organic matter content (Haynes and Francis, 1990). For example, wheat is a high nutrient demanding crop which removes a substantial amount of nutrients (specifically nitrogen) from the soil (Pattinson and Pattinson, 1985), leaving it less fertile than it was. Following this crop with either peas or clover pasture which are known for their high nitrogen fixing rates (Nguyen et al., 1995), will remedy the nutrient loss, improve organic matter of the soil, and will leave the land ready for the next cereal crop. When farmland paddock is in its clover-grass pasture phase, the fire danger will be relatively low given the low flammability rankings of pasture grasses and legumes. However, when it is in its arable cropping phase (wheat, barley etc.), the fire danger of the farm increases due to its high flammability ranking and will hence need to be surrounded by a range of low flammability crops (Figure 11). If a given farm is likely to be particularly fire-prone (due to climate, topography, or surrounding fuels), extra care may need to be taken when allocating paddocks to higher flammability cereal crops.

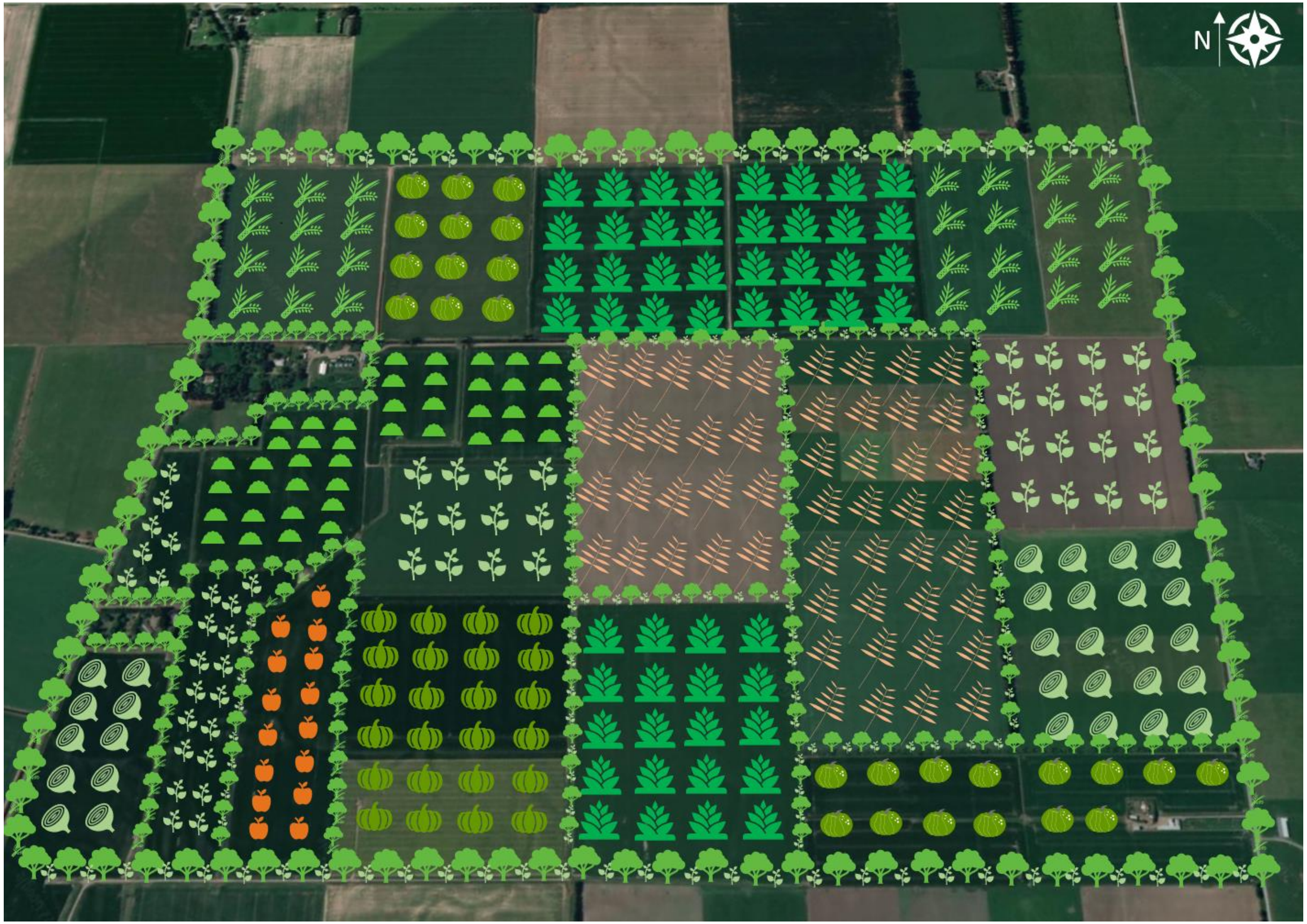
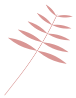


Figure 11: A fire-wise mixed cropping farm system (showing a general variety of crops and cropping location and is not restricted to any one season of a year) based in the Canterbury Plains.

Example key:

Icon	**Crop type**	**List of species that could be used with their flammability rankings**
	Low flammability native tree/shelter belt/native shrubs species	‘Low’: Broadleaf (*Griselinia littoralis*), Five-finger (*Pseudopanax arboreus*), Karamū (*Coprosma robusta*), Kōtukutuku (*Fuchsia excorticata*), Karaka (*Corynocarpus laevigatus*), New Zealand Flax (*Phormium tenax*), Fiordland grass tree (*Dracophyllum fiordense*), Kaikōmako (*Pennantia corymbose*), Pittosporum divaricatum (*Pittosporum divaricatum*), Weeping Matipo (*Myrsine divaricate*), Coprosma spp. (*Coprosma cheesemanii, C. crassifolia*), Mingimingi (*Coprosma propinqua*), Māhoe (whitey wood) (*Melicytus ramiflorus*). ‘Very Low’: Hangehange (*Geniostoma ligustrifolium*), Kawakawa (*Piper excelsum*), Māpou/Red Matipo (*Myrsine australis*), Hūpiro (*Coprosma foetidissima*), Mirror bush (*Coprosma repens/ C. serrulata*), Poroporo (*Solanum laciniatum*)
	Moderately High/Moderate flammability cereal crop species	‘Moderately high’: Wheat (*Triticum aestivum* L.). ‘Moderate’: Barley (*Hordeum vulgare* L.), Oats (*Avena fatua* L.), Popcorn (*Zea mays* var. *everta*),
	Low flammability forage crop species	‘Very Low’: Kale (*Brassica oleracea* L. var. *Sabellica),* Fodder beet *(Beta vulgaris 'Mangelwurzel'),* Rapeseed *(Brassica napus* L.)
	Low flammability pasture grass species	‘Low’: Pasture Brome (*Bromus valdivianus* Phil.) ‘Very Low’: Cocksfoot *(Dactylis glomerata* L.), Italian ryegrass (*Lolium multiflorum* Lam.), , Perennial ryegrass (*Lolium perenne* L.), Phalaris/bulbous canary-grass (*Phalaris aquatica* L.), Prairie grass (*Bromus willdenowii* Kunth.), Tall Fescue (*Festuca arundinacea* Schreb.), Timothy grass (*Phleum pratense* L.)
	High/Moderately High flammability fruit crops/orchards	‘High’: common pear (*Pyrus communis* L.), ‘Moderately high’: Apples (*Malus domestica.* ‘Braeburn’, *Malus domestica.* ‘Royal Gala’), ‘Moderate’: olives (*Olea europaea. ‘*Barnea’), raspberries (*Rubus idaeus* L.)

	Low flammability pasture legume and grazing herb species	<u>'Very low'</u>: Caucasian clover (*Trifolium ambiguum* M.Bieb), Coronilla/crown vetch (*Securigera varia* (L.) Lassen), hairy canary-clover (*Dorycnium hirsutum* L.), lotus/big trefoil (*Lotus pedunculatus* Cav.), lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), chicory (*Cichorium intybus* L.), ribwort plantain (*Plantago lanceolata* L.).
	Low flammability vegetable crop species	<u>'Very low'</u>: Squash (*Cucurbita spp.* L. (*maxima, moschata, pepo*)), potatoes (*Solanum tuberosum* L.), spring onions (*Allium fistulosum* L.), dwarf snow peas (*Pisum sativum* L.), bell peppers (*Capsicum annum* L.).

4.5 Future research

The use of shoot flammability measurements to examine flammability of crop and pasture species is still in its early stages, but the research described in this thesis shows the promise it holds. Recommendations for further research include testing a wider range of species that occur on agricultural land, introducing a seasonal component to testing and scaling the study up to field tests.

Though this study is the first of its kind in measuring the flammability of 47 crop and pasture species (Chapter 2), a wider range of species that occur on agricultural land will need to be tested, especially on rural land other than Canterbury, to gain a better understanding of flammable farms throughout New Zealand, and globally. Flammability testing should not be limited to just crop and pasture species but should also include any other plant species that usually occur on rural land.

Plant flammability is known to change with seasons, possibly resulting in different fire severities and intensities (Añón et al., 1995), especially because plant moisture varies seasonally and this can directly influence plant flammability (Owens et al., 1998). Therefore, introducing a seasonal component (such as pre-harvest and post-harvest, and during different phenological stages of crops, such as cereals) to the testing of species will be vital in understanding how flammable crops are under different environmental conditions.

While measuring the shoot-level and whole plant flammability of plants likely provides an accurate comparison of relative canopy-level flammability in the field (Wyse et al., 2016; Alam et al. 2020), other methodologies such as field-based studies are required to gain a better understanding of crop flammability and fire behaviour. There are a few studies that have examined flammability of crops in the field. For instance, in an unpublished preprint, Fu et al. (2021) used fire modelling to describe how banana crops could be used as edible fire buffers in California, while Cruz et al., (2020) investigated fire behaviour of wheat crop under different crop conditions (unharvested, harvested and baled) in wheat plots in Australia. Many more such field-level experiments are required to gain a comprehensive understanding of how fire behaves when a range of crops are involved, which will help farmers and rural land owners to design their land accordingly.

4.6 Conclusions

My study evaluated the flammability of various species prevalent in agricultural landscapes in Canterbury, New Zealand and demonstrated how the knowledge of flammability could be utilised to evaluate fire risks and design our landscape to mitigate wildfires. By identifying species with varying levels of flammability, this study will help farmers and landowners remodel their farms so that they can plant low-flammability species in places they consider to be high fire hazards, thus helping achieve a key goal of Kelly et al. (2020) and implement diverse agricultural landscapes to mitigate wildfires.

Overall, this information will help us better understand how fire regimes vary over time and space in agricultural landscapes and will enable us to take appropriate precautions against wildfires in the era of rapid climate change and increasingly destructive wildfires in New Zealand and worldwide.

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Appendix A

List of the 316 species included in Chapter 3 of this thesis. Taxonomy follows the New Zealand Plant Conservation Network (http://www.nzpcn.org.nz) and Royal Botanic Gardens Kew's Plants of the World Online (https://powo.science.kew.org/).

Species	Code	N	Family	Order	Class	Rank
Acacia dealbata	ACAdea	14	Fabaceae	Fabales	Rosid I	Mod/High
Acacia melanoxylon	ACAmel	8	Fabaceae	Fabales	Rosid I	Mod/High
Acacia pravissima	ACApra	6	Fabaceae	Fabales	Rosid I	Mod/High
Acaena caesiiglauca	ACAcae	8	Rosaceae	Rosales	Rosid I	Moderate
Acca sellowaiana	ACCsel	8	Myrtaceae	Myrtales	Rosid II	Mod/High
Achillea millefolium	ACHmil	8	Asteraceae	Asterales	Asterid II	Very Low
Aciphylla aurea	ACIaur	8	Apiaceae	Apiales	Asterid II	Very High
Aesculus hippocastanum	AEShip	6	Sapindaceae	Sapindales	Rosid II	Moderate
Agapanthus Baby Pete	AGAbab	6	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Agapanthus Peter Pan	AGApet	8	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Agapanthus Tinkerbell	AGAtin	5	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Agapanthus praecox	AGApra	8	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Agathis australis	AGAaus	14	Araucariaceae	Pinales	Pinophyta	Low/Mod
Agrostis capillaris	AGRcap	8	Poaceae	Poales	Commelinids	Low
Agrostis muelleriana	AGRmue	8	Poaceae	Poales	Commelinids	Very Low
Alectryon excelsus	ALEexc	8	Sapindaceae	Sapindales	Rosid II	Mod/High
Allium fistulosum	ALLfis	8	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Ammophila arenaria	AMMare	8	Poaceae	Poales	Commelinids	High
Anisotome aromatica	ANIaro	15	Apiaceae	Apiales	Asterid II	Very Low
Anisotome flexuosa	ANIfle	8	Apiaceae	Apiales	Asterid II	Low/Mod
Anisotome haastii	ANIhaa	6	Apiaceae	Apiales	Asterid II	Very Low
Anthoxanthum odoratum	ANTodo	8	Poaceae	Poales	Commelinids	Moderate
Apodasmia similis	APOsim	8	Restionaceae	Poales	Commelinids	Moderate

Aporostylis bifolia	APObif	6	Orchidaceae	Asparagales	Lilioid monocots	Very Low
Arbutus unedo	ARBune	6	Ericaceae	Ericales	Ericales	Mod/High
Aristotelia fruticosa	ARIfru	8	Elaeocarpaceae	Oxalidales	Rosid I	Low
Aristotelia serrata	ARIser	25	Elaeocarpaceae	Oxalidales	Rosid I	Low
Astelia nervosa	ASTner	6	Asteliaceae	Asparagales	Lilioid monocots	Low
Avena fatua	AVEfat	8	Poaceae	Poales	Commelinids	Moderate
Beilschmiedia tarairi	BEItar	8	Lauraceae	Laurales	Magnoliidae	Low/Mod
Beilschmiedia tawa	BEItaw	14	Lauraceae	Laurales	Magnoliidae	Low/Mod
Beta vulgaris 'Mangelwurzel'	BETvul	8	Amaranthaceae	Caryophyllales	Rosid II	Very Low
Betula pendula	BETpen	6	Betulaceae	Fagales	Rosid I	Moderate
Blechnum minus	BLEmin	6	Blechnaceae	Polypodiales	Polypodiopsida	Moderate
Blechnum penna-marina	BLEpen	14	Blechnaceae	Athyriales	Polypodiopsida	Low
Brachyglottis bellidioides	BRAbel	6	Asteraceae	Asterales	Asterid II	Very Low
Brachyglottis elaeagnifolia	BRAela	6	Asteraceae	Asterales	Asterid II	Very Low
Brachyglottis repanda	BRArep	6	Asteraceae	Asterales	Asterid II	Mod/High
Brachyscome longiscapa	BRAlon	8	Asteraceae	Asterales	Asterid II	Very Low
Brassica napus	BRAnap	8	Brassicaceae	Brassicales	Rosid II	Very Low
Brassica oleracea var. sabellica	BRAole	8	Brassicaceae	Brassicales	Rosid II	Very Low
Bromus valdivianus	BROhor	8	Poaceae	Poales	Commelinids	Low
Bromus willdenowii	BROval	8	Poaceae	Poales	Commelinids	Very Low
Bromus hordeaceus	BROwil	8	Poaceae	Poales	Commelinids	Very Low
Callistemon rigidus	CALrig	8	Myrtaceae	Myrtales	Rosid II	Mod/High
Camellia sasanqua Setsugekka	CAMsas	4	Theaceae	Ericales	Ericales	Moderate
Capsicum annum	CAPann	8	Solanaceae	Solanales	Asterid I	Very Low
Carex coriaceae	CARcor	6	Cyperaceae	Poales	Commelinids	Mod/High
Carex corynoidea	CARcory	8	Cyperaceae	Poales	Commelinids	Low
Carex wakatipu	CARwak	8	Cyperaceae	Poales	Commelinids	Low
Carmichaelia australis	CARaus	6	Fabaceae	Fabales	Rosid I	High
Carpha alpina	CARalp	6	Cyperaceae	Poales	Commelinids	Low/Mod
Carpodetus serratus	CARser	30	Rousseaceae	Asterales	Asterid II	Low

Celmisia armstrongii	CELarm	6	Asteraceae	Asterales	Asterid II	Mod/High
Celmisia discolor	CELdis	6	Asteraceae	Asterales	Asterid II	Mod/High
Celmisia gracilenta	CELgra	16	Asteraceae	Asterales	Asterid II	Low
Celmisia verbascifolia	CELver	6	Asteraceae	Asterales	Asterid II	Low/Mod
Chamaecytisus palmensis	CHApal	14	Fabaceae	Fabales	Rosid I	Low/Mod
Chenopodium album	CHEalb	8	Amaranthaceae	Caryophyllales	Rosid II	Low
Chionochloa conspicua	CHIcon	6	Poaceae	Poales	Commelinids	Moderate
Chionochloa macra	CHImac	16	Poaceae	Poales	Commelinids	Very High
Chionochloa rigida	CHIrig	8	Poaceae	Poales	Commelinids	Very High
Chionochloa rubra	CHIrub	7	Poaceae	Poales	Commelinids	High
Choisya ternata	CHOter	6	Rutaceae	Sapindales	Rosid II	Low/Mod
Cichorium intybus	CICint	8	Asteraceae	Asterales	Asterid II	Very Low
Citrus limon	CITlim	6	Rutaceae	Sapindales	Rosid II	Low/Mod
Clivia miniata	CLImin	8	Amaryllidaceae	Asparagales	Lilioid monocots	Very Low
Coprosma arborea	COParb	8	Rubiaceae	Gentianales	Asterid I	Low
Coprosma cheesemanii	COPche	6	Rubiaceae	Gentianales	Asterid I	Low
Coprosma crassifolia	COPcra	8	Rubiaceae	Gentianales	Asterid I	Low
Coprosma depressa	COPdep	5	Rubiaceae	Gentianales	Asterid I	Low/Mod
Coprosma dumosa	COPdum	15	Rubiaceae	Gentianales	Asterid I	Low/Mod
Coprosma foetidissima	COPfoe	5	Rubiaceae	Gentianales	Asterid I	Very Low
Coprosma propinqua	COPpro	14	Rubiaceae	Gentianales	Asterid I	Low
Coprosma pseudocuneata	COPpse	6	Rubiaceae	Gentianales	Asterid I	Low/Mod
Coprosma repens	COPrep	8	Rubiaceae	Gentianales	Asterid I	Very Low
Coprosma robusta	COProb	22	Rubiaceae	Gentianales	Asterid I	Low
Coprosma serrulata	COPser	6	Rubiaceae	Gentianales	Asterid I	Very Low
Cordyline australis	CORaus	8	Asparagaceae	Asparagales	Lilioid monocots	Low/Mod
Coriaria arborea	CORarb	6	Coriariaceae	Cucurbitales	Rosid I	Mod/High
Corokia buddleioides	CORbud	10	Argophyllaceae	Asterales	Asterid II	Mod/High
Corokia cotoneaster	CORcot	8	Argophyllaceae	Asterales	Asterid II	Low/Mod
Corynocarpus laevigatus	CORlae	8	Corynocarpaceae	Cucurbitales	Rosid I	Low

Cotoneaster spp	COTspp	6	Rosaceae	Rosales	Rosid I	Low
Crepis capillaris	CREcap	8	Asteraceae	Asterales	Asterid II	Very Low
Crocosmia crocosmiiflora	CROcro	8	Iridaceae	Asparagales	Lilioid monocots	Very Low
Cucurbita spp. (maxima, moschata, pepo)	CUCspp	8	Cucurbitaceae	Cucurbitales	Rosid I	Low
Cupressus macrocarpa	CUPmac	11	Cupressaceae	Pinales	Pinophyta	Moderate
Cyathea dealbata	CYAdea	8	Cyatheaceae	Cyatheales	Polypodiopsida	Moderate
Cyathea medullaris	CYAmed	8	Cyatheaceae	Cyatheales	Polypodiopsida	Low/Mod
Cytisus scoparius	CYTsco	14	Fabaceae	Fabales	Rosid I	Low/Mod
Dacrycarpus dacrydioides	DACdac	14	Podocarpaceae	Pinales	Pinophyta	Moderate
Dacrydium cupressinum	DACcup	8	Podocarpaceae	Pinales	Pinophyta	Mod/High
Dactylis glomerata	DACglo	8	Poaceae	Poales	Commelinids	Very Low
Deyeuxia avenoides	DEYave	8	Poaceae	Poales	Commelinids	Mod/High
Dianthus armeria	DIAarm	6	Caryophyllaceae	Caryophyllales	Rosid II	Very Low
Dicksonia squarrosa	DICsqu	8	Dicksoniaceae	Cyatheales	Polypodiopsida	Mod/High
Discaria toumatou	DIStou	17	Rhamnaceae	Rosales	Rosid I	Moderate
Dodonaea viscosa	DODvis	15	Sapindaceae	Sapindales	Rosid II	Low/Mod
Dolichoglottis lyallii	DOLlya	6	Asteraceae	Asterales	Asterid II	Very Low
Dorycnium hirsutum	DORhir	8	Fabaceae	Fabales	Rosid I	Low
Dracophyllum acerosum	DRAace	23	Ericaceae	Ericales	Ericales	High
Dracophyllum densum	DRAden	8	Ericaceae	Ericales	Ericales	Very High
Dracophyllum elegantissima	DRAele	8	Ericaceae	Ericales	Ericales	Moderate
Dracophyllum filifolium	DRAfil	8	Ericaceae	Ericales	Ericales	High
Dracophyllum fiordense	DRAfio	8	Ericaceae	Ericales	Ericales	Low
Dracophyllum kirkii	DRAkir	8	Ericaceae	Ericales	Ericales	High
Dracophyllum latifolium	DRAlat	8	Ericaceae	Ericales	Ericales	High
Dracophyllum longifolium	DRAlon	51	Ericaceae	Ericales	Ericales	Mod/High
Dracophyllum marmoricola	DRAmar	8	Ericaceae	Ericales	Ericales	High
Dracophyllum menzisii	DRAmen	8	Ericaceae	Ericales	Ericales	High
Dracophyllum muscoides	DRAmus	8	Ericaceae	Ericales	Ericales	Moderate
Dracophyllum oliveri	DRAoli	8	Ericaceae	Ericales	Ericales	High

Dracophyllum ophioliticus	DRAoph	8	Ericaceae	Ericales	Ericales	Moderate
Dracophyllum palustris	DRApal	7	Ericaceae	Ericales	Ericales	High
Dracophyllum pronum	DRApro	7	Ericaceae	Ericales	Ericales	Very High
Dracophyllum recurvum	DRArec	8	Ericaceae	Ericales	Ericales	Mod/High
Dracophyllum rosmanrinifolium	DRAros	62	Ericaceae	Ericales	Ericales	High
Dracophyllum sinclairii	DRAsin	8	Ericaceae	Ericales	Ericales	High
Dracophyllum subulatum	DRAsub	8	Ericaceae	Ericales	Ericales	High
Dracophyllum townsonii	DRAtow	8	Ericaceae	Ericales	Ericales	Mod/High
Dracophyllum traversii	DRAtra	13	Ericaceae	Ericales	Ericales	Low/Mod
Dracophyllum trimorphus	DRAtri	10	Ericaceae	Ericales	Ericales	High
Dracophyllum uniflorum	DRAuni	6	Ericaceae	Ericales	Ericales	Moderate
Dysoxylum spectabile	DYSspe	8	Meliaceae	Sapindales	Rosid II	Low
Echium vulgare	ECHvul	6	Boraginaceae	Boraginales	Magnoliopsida	Low/Mod
Elaeocarpus hookerianus	ELAhoo	3	Elaeocarpaceae	Oxalidales	Rosid I	Low/Mod
Elymus solandri	ELYsol	8	Poaceae	Poales	Commelinids	Mod/High
Epilobium alsinoides	EPIals	8	Onagraceae	Myrtales	Rosid II	Very Low
Eucalyptus cinerea	EUCcin	6	Myrtaceae	Myrtales	Rosid II	Mod/High
Eucalyptus viminalis	EUCvim	30	Myrtaceae	Myrtales	Rosid II	Mod/High
Euphrasia dyeri	EUPdye	8	Orobanchaceae	Lamiales	Asterid I	Low
Fagus sylvatica	FAGsyl	6	Fagaceae	Fagales	Rosid I	Mod/High
Farfugium japonicum var. giganteum	FARjap	8	Asteraceae	Asterales	Asterid II	Very Low
Festuca novae-zelandiae	FESnov	8	Poaceae	Poales	Commelinids	High
Festuca arundinacea	FESaru	8	Poaceae	Poales	Commelinids	Very Low
Fraxinus pennsylvanica	FRApen	6	Oleaceae	Lamiales	Asterid I	Mod/High
Fuchsia excorticata	FUCexc	30	Onagraceae	Myrtales	Rosid II	Low
Fuschia excorticata x perscandens	FUCexc.Per	5	Onagraceae	Myrtales	Rosid II	Low/Mod
Fuscospora cliffortioides	FUScli	26	Nothofagaceae	Fagales	Rosid I	Mod/High
Fuscospora fusca	FUSfus	47	Nothofagaceae	Fagales	Rosid I	Low/Mod
Gaultheria depressa	GAUdep	8	Ericaceae	Ericales	Ericales	High
Gaultheria rupestris	GAUrup	6	Ericaceae	Ericales	Ericales	Moderate

Geniostoma ligustrifolium	GENlig	8	Loganiaceae	Gentianales	Asterid I	Very Low
Geranium microphyllum	GERmic	8	Geraniaceae	Gentianales	Asterid I	Very Low
Geranium sessiliflorum	GERses	8	Geraniaceae	Gentianales	Asterid I	Low
Geum leiospermum	GEUlei	8	Rosaceae	Rosales	Rosid I	Very Low
Ginkgo biloba	GINbil	6	Ginkgoaceae	Ginkgoales	Ginkgoales	Low/Mod
Gonocarpus aggregatus	GONagg	6	Haloragaceae	Saxifragales	Magnoliopsida	Very Low
Griselinia littoralis	GRIlit	29	Griseliniaceae	Apiales	Asterid II	Low
Hakea sericea	HAKser	8	Proteaceae	Proteales	Proteales	Mod/High
Hebe salicifolia	HEBsal	10	Plantaginaceae	Lamiales	Asterid I	Low/Mod
Hebe Wiri Mist	HEBwir	8	Plantaginaceae	Lamiales	Asterid I	Moderate
Hedycarya arborea	HEDarb	6	Monimiaceae	Laurales	Magnoliidae	Low/Mod
Helichrysum filicaule	HELfil	8	Asteraceae	Asterales	Asterid II	Very Low
Hieracium lepidulum	HIElep	14	Asteraceae	Asterales	Asterid II	Low
Hieracium pilosella	HIEpil	8	Asteraceae	Asterales	Asterid II	Very Low
Hieracium praealtum	HIEpra	8	Asteraceae	Asterales	Asterid II	Very Low
Hoheria angustifolia	HOHang	26	Malvaceae	Malvales	Rosid II	Low/Mod
Hordeum vulgare	HORvul	8	Poaceae	Poales	Commelinids	Low/Mod
Hydrocotyle novae-zeelandiae	HYDnov	14	Araliaceae	Apiales	Asterid II	Very Low
Hypochaeris radicata	HYPrad	14	Asteraceae	Asterales	Asterid II	Very Low
Juncus gregiflorus	JUNgre	6	Juncaceae	Poales	Commelinids	Mod/High
Kelleria dieffenbachii	KELdie	8	Thymelaeaceae	Malvales	Rosid II	Low
Knightia excelsa	KNIexc	8	Proteaceae	Proteales	Proteales	Moderate
Kunzea ericoides	KUNeri	52	Myrtaceae	Myrtales	Rosid II	Mod/High
Kunzea robusta	KUNrob	36	Myrtaceae	Myrtales	Rosid II	High
Lagenophora cuneata	LAGcun	8	Asteraceae	Asterales	Asterid II	Very Low
Laurus nobilis	LAUnob	5	Lauraceae	Laurales	Magnoliidae	Moderate
Leptinella pectinata	LEPpec	8	Asteraceae	Asterales	Asterid II	Very Low
Leptospermum scoparium	LEPsco	14	Myrtaceae	Myrtales	Rosid II	Mod/High
Leucopogon colensoi	LEUcol	6	Ericaceae	Ericales	Ericales	High
Leucopogon fasciculatus	LEUfas	9	Ericaceae	Ericales	Ericales	Moderate

Leucopogon fraseri	LEUfra	7	Ericaceae	Ericales	Ericales	Moderate
Leycesteria formosa	LEYfor	6	Caprifoliaceae	Dipsacales	Asterid II	Mod/High
Ligustrum lucidum	LIGluc	6	Oleaceae	Lamiales	Asterid I	Low/Mod
Liquidambar styraciflua	LIQsty	6	Altingiaceae	Saxifragales	Magnoliopsida	Moderate
Lolium multiflorum	LOLmul	8	Poaceae	Poales	Commelinids	Very Low
Lolium perenne	LOLper	8	Poaceae	Poales	Commelinids	Very Low
Lophozonia menziesii	LOPmen	20	Nothofagaceae	Fagales	Rosid I	High
Lotus pedunculatus	LOTped	8	Fabaceae	Fabales	Rosid I	Very Low
Lupinus arboreus	LUParb	8	Fabaceae	Fabales	Rosid I	Low
Luzula pumila	LUZpum	8	Juncaceae	Poales	Commelinids	Mod/High
Luzula rufa	LUZruf	8	Juncaceae	Poales	Commelinids	Very Low
Lycopodium fastigiatum	LYCfas	14	Lycopodiaceae	Lycopodiales	Lycopodiophyta	Very Low
Lycopodium scariosum	LYCsca	6	Lycopodiaceae	Lycopodiales	Lycopodiophyta	Mod/High
Magnolia grandiflora	MAGgra	6	Magnoliaceae	Magnoliales	Magnoliidae	Moderate
Malus domestica	MALdom	4	Rosaceae	Rosales	Rosid I	Mod/High
Malus domestica. Braeburn	MALdom.Bra	8	Rosaceae	Rosales	Rosid I	Mod/High
Malus domestica. Granny Smith	MALdom.Roy	8	Rosaceae	Rosales	Rosid I	Mod/High
Malus domestica. Royal Gala	MALgra	8	Rosaceae	Rosales	Rosid I	Mod/High
Malva neglecta	MALneg	8	Malvaceae	Malvales	Rosid II	Very Low
Maytenus boaria	MAYboa	6	Celastraceae	Celastrales	Rosid I	Moderate
Medicago sativa	MEDsat	8	Fabaceae	Fabales	Rosid I	Very Low
Melicytus crassifolius	MELcra	8	Violaceae	Malpighiales	Rosid I	Low/Mod
Melicytus ramiflorus	MELram	31	Violaceae	Malpighiales	Rosid I	Low
Metrosideros excelsa	METexc	14	Myrtaceae	Myrtales	Rosid II	Low/Mod
Metrosideros fulgens	METful	8	Myrtaceae	Myrtales	Rosid II	Low/Mod
Muehlenbeckia australis	MUEaus	18	Polygonaceae	Caryophyllales	Rosid II	Low
Muehlenbeckia axillaris	MUEaxi	6	Polygonaceae	Caryophyllales	Rosid II	Mod/High
Myoporum laetum	MYOlae	12	Scrophulariaceae	Lamiales	Asterid I	Low/Mod
Myrsine australis	MYRaus	8	Primulaceae	Ericales	Ericales	Very Low
Myrsine divaricata	MYRdiv	6	Primulaceae	Ericales	Ericales	Low

Myrsine nummularia	MYRnum	6	Primulaceae	Ericales	Ericales	Moderate
Nematolepis squamea	NEMsqu	12	Rutaceae	Sapindales	Rosid II	Low/Mod
Nestegis lanceolata	NESlan	8	Oleaceae	Lamiales	Asterid I	Moderate
Olea europaea Barnea	OLEeur.B	8	Oleaceae	Lamiales	Asterid I	Moderate
Olea europaeus	OLEeur	8	Oleaceae	Lamiales	Asterid I	Moderate
Olearia furfuraceae	OLEfur	8	Asteraceae	Asterales	Asterid II	Moderate
Olearia paniculata	OLEpan	6	Asteraceae	Asterales	Asterid II	Moderate
Olearia traversiorum	OLEtra	12	Asteraceae	Asterales	Asterid II	Low/Mod
Ophiopogon Black Dragon	OPHbla	8	Asparagaceae	Asparagales	Lilioid monocots	Very Low
Ourisia macrophylla	OURmap	6	Plantaginaceae	Lamiales	Asterid I	Very Low
Ozothamnus leptophyllus	OZOlep	6	Asteraceae	Asterales	Asterid II	Moderate
Pennantia corymbosa	PENcor	13	Pennantiaceae	Apiales	Asterid II	Low
Pentachondra pumila	PENpum	6	Ericaceae	Ericales	Ericales	Low
Phalaris aquatica	PHAaqu	8	Poaceae	Poales	Commelinids	Very Low
Phleum pratense	PHLpra	8	Poaceae	Poales	Commelinids	Very Low
Phormium cookianum	PHOcoo	14	Asphodelaceae	Asparagales	Lilioid monocots	Moderate
Phormium Dark Delight	PHOdar	8	Asphodelaceae	Asparagales	Lilioid monocots	Very Low
Phormium tenax	PHOten	8	Asphodelaceae	Asparagales	Lilioid monocots	Low
Photinia Red Robin	PHOred	8	Rosaceae	Rosales	Rosid I	Low/Mod
Phyllocladus alpinus	PHYalp	6	Podocarpaceae	Pinales	Pinophyta	High
Phyllocladus trichomanioides	PHYtri	8	Podocarpaceae	Pinales	Pinophyta	Moderate
Phytolacca octandra	PHYoct	6	Phytolaccaceae	Caryophyllales	Rosid II	Very Low
Pimelea oreophila	PIMore	9	Thymelaeaceae	Malvales	Rosid II	Mod/High
Pinus arizonica	PINari	7	Pinaceae	Pinales	Pinophyta	High
Pinus contorta	PINcon	8	Pinaceae	Pinales	Pinophyta	Low
Pinus coulteri	PINcou	8	Pinaceae	Pinales	Pinophyta	Mod/High
Pinus nigra	PINnig	15	Pinaceae	Pinales	Pinophyta	Moderate
Pinus palustris	PINpal	4	Pinaceae	Pinales	Pinophyta	High
Pinus ponderosa	PINpon	8	Pinaceae	Pinales	Pinophyta	Very High
Pinus radiata	PINrad	45	Pinaceae	Pinales	Pinophyta	Low/Mod

Pinus sylvestris	PINsyl	9	Pinaceae	Pinales	Pinophyta	Mod/High
Pinus wallachiana	PINwal	8	Pinaceae	Pinales	Pinophyta	Mod/High
Piper excelsum	PIPexc	6	Piperaceae	Piperales	Magnoliidae	Very Low
Pisum sativum	PISsat	8	Fabaceae	Fabales	Rosid I	Very Low
Pittosporum crassifolium	PITcra	14	Pittosporaceae	Apiales	Asterid II	Low/Mod
Pittosporum divaricatum	PITdiv	14	Pittosporaceae	Apiales	Asterid II	Low
Pittosporum eugenioides	PITeug	26	Pittosporaceae	Apiales	Asterid II	Low/Mod
Pittosporum tenuifolium	PITten	34	Pittosporaceae	Apiales	Asterid II	Low/Mod
Plagianthus regius	PLAreg	21	Malvaceae	Malvales	Rosid II	Low
Plantago lanceolata	PLAlan	8	Plantaginaceae	Lamiales	Asterid I	Very Low
Poa cita	POAcit	6	Poaceae	Poales	Commelinids	Very High
Poa colensoi	POAcol	14	Poaceae	Poales	Commelinids	Moderate
Podocarpus cunninghamii	PODcun	6	Podocarpaceae	Pinales	Pinophyta	Moderate
Podocarpus hallii	PODhal	8	Podocarpaceae	Pinales	Pinophyta	Moderate
Podocarpus nivalis	PODniv	6	Podocarpaceae	Pinales	Pinophyta	Moderate
Podocarpus totara	PODtot	14	Podocarpaceae	Pinales	Pinophyta	Moderate
Polystichum vestitum	POLves	11	Dryopteridaceae	Polypodiales	Polypodiopsida	Low/Mod
Pomaderris kumaraho	POMkum	8	Rhamnaceae	Rosales	Rosid I	High
Populus nigra	POPnig	33	Salicaceae	Malpighiales	Rosid I	Low
Populus trichocarpa	POPtri	6	Salicaceae	Malpighiales	Rosid I	Low/Mod
Protea neriifolia	PROner	6	Proteaceae	Proteales	Proteales	Moderate
Prumnopitys ferruginea	PRUfer	8	Podocarpaceae	Pinales	Pinophyta	Low/Mod
Prumnopitys taxifolia	PRUtax	10	Podocarpaceae	Pinales	Pinophyta	Low/Mod
Prunus yedoensis	PRUyed	8	Rosaceae	Rosales	Rosid I	Mod/High
Prunus Kanzan	PRUkan	12	Rosaceae	Rosales	Rosid I	Moderate
Prunus laurocerasus	PRUlau	6	Rosaceae	Rosales	Rosid I	Low
Pseudopanax arboreus	PSEarb	27	Araliaceae	Apiales	Asterid II	Low
Pseudopanax colensoi	PSEcole	12	Araliaceae	Apiales	Asterid II	Low
Pseudopanax crassifolius	PSEcra	24	Araliaceae	Apiales	Asterid II	Very Low
Pseudotsuga menziesii	PSEmen	8	Pinaceae	Pinales	Pinophyta	Moderate

Pseudowintera colorata	PSEcol	18	Winteraceae	Canellales	Magnoliidae	Mod/High
Pteridium esculentum	PTEesc	14	Dennstaedtiaceae	Polypodiales	Polypodiopsida	Moderate
Pyrus communis	PYRcom	8	Rosaceae	Rosales	Rosid I	High
Pyrus spp.	PYRspp	7	Rosaceae	Rosales	Rosid I	Mod/High
Quercus ilex	QUEile	12	Fagaceae	Fagales	Rosid I	Moderate
Quersus robur	QUErob	6	Fagaceae	Fagales	Rosid I	High
Raoulia grandiflora	RAOgra	8	Asteraceae	Asterales	Asterid II	Very Low
Raoulia subsericea	RAOsub	9	Asteraceae	Asterales	Asterid II	Mod/High
Ribes uva-crispa	RIBuva	8	Grossulariaceae	Saxifragales	Magnoliopsida	Low
Ripogonum scandens	RIPsca	8	Ripogonaceae	Liliales	Lilioid monocots	Low
Rosa rubiginosa	ROSrub	8	Rosaceae	Rosales	Rosid I	Low
Rosmarinus officinalis	ROSoff	7	Lamiaceae	Lamiales	Asterid I	Low/Mod
Rubus cissoides	RUBcis	9	Rosaceae	Rosales	Rosid I	Low/Mod
Rubus fruticosus agg.	RUBfru	8	Rosaceae	Rosales	Rosid I	Low/Mod
Rubus idaeus	RUBida	8	Rosaceae	Rosales	Rosid I	Mod/High
Rumex acetosella	RUMace	10	Polygonaceae	Caryophyllales	Rosid II	Low
Rumex obtusifolius	RUMobt	8	Polygonaceae	Caryophyllales	Rosid II	Very Low
Rytidosperma setifolium	RYTset	8	Poaceae	Poales	Commelinids	Low
Salix fragilis	SALfra	7	Salicaceae	Malpighiales	Rosid I	Moderate
Salix matsudana	SALmat	6	Salicaceae	Malpighiales	Rosid I	Moderate
Salix sepulcralis Chrysocoma	SALsep	4	Salicaceae	Malpighiales	Rosid I	Low/Mod
Schoenus pauciflorus	SCHpau	6	Cyperaceae	Poales	Commelinids	Low/Mod
Scleranthus uniflorus	SCLuni	8	Caryophyllaceae	Caryophyllales	Rosid II	Moderate
Securigera varia	SECvar	8	Fabaceae	Fabales	Rosid I	Very Low
Solanum laciniatum	SOLlac	14	Solanaceae	Solanales	Asterid I	Very Low
Solanum tuberosum	SOLtub	8	Solanaceae	Solanales	Asterid I	Very Low
Sophora microphylla	SOPmic	10	Fagaceae	Fagales	Rosid I	Low
Sysygium smithii	SYZsmi	8	Myrtaceae	Myrtales	Rosid II	Moderate
Trachelospermum jasminoides	TRAjas	6	Apocynaceae	Gentianales	Asterid I	Low/Mod
Trifolium ambiguum	TRIarv	8	Fabaceae	Fabales	Rosid I	Very Low

Trifolium arvense	TRIpra	16	Fabaceae	Fabales	Rosid I	Very Low
Trifolium pratense	TRIrep	16	Fabaceae	Fabales	Rosid I	Very Low
Trifolium repens	TRIamb	8	Fabaceae	Fabales	Rosid I	Very Low
Triticum aestivum	TRIaes	8	Poaceae	Poales	Commelinids	Mod/High
Ulex europaeus	ULEeur	18	Fabaceae	Fabales	Rosid I	High
Vaccinium spp.	VACspp	8	Ericaceae	Ericales	Ericales	Moderate
Verbascum thapsus	VERtha	6	Scrophulariaceae	Lamiales	Asterid I	Low/Mod
Veronica canterburiensis	VERcan	6	Plantaginaceae	Lamiales	Asterid I	Moderate
Veronica subalpina	VERsub	6	Plantaginaceae	Lamiales	Asterid I	Low/Mod
Vibranum tinus	VIBtin	6	Adoxaceae	Dipsacales	Asterid II	Mod/High
Viola cunninghamii	VIOcun	8	Violaceae	Malpighiales	Rosid I	Very Low
Viola lyallii	VIOlya	6	Violaceae	Malpighiales	Rosid I	Very Low
Vitex lucens	VITluc	8	Lamiaceae	Lamiales	Asterid I	Low/Mod
Vitis vinifera. Chardonnay	VITvin.Chardonnay	8	Vitaceae	Vitales	Magnoliopsida	Low
Vitis vinifera. Merlot	VITvin.Mer	8	Vitaceae	Vitales	Magnoliopsida	Low
Vitis vinifera. Pinot Gris	VITvin.Gri	8	Vitaceae	Vitales	Magnoliopsida	Low/Mod
Vitis vinifera. Pinot Noir	VITvin.Noi	8	Vitaceae	Vitales	Magnoliopsida	Very Low
Vitis vinifera. Reisling	VITvin.Rei	8	Vitaceae	Vitales	Magnoliopsida	Very Low
Vitis vinifera. Sauvignon Blanc	VITvin.Sau	8	Vitaceae	Vitales	Magnoliopsida	Low
Wahlenbergia albomarginata	WAHalb	8	Campanulaceae	Asterales	Asterid II	Very Low
Weinmania racemosa	WEIrac	8	Cunoniaceae	Oxalidales	Rosid I	Moderate
Zea mays	ZEAmay	8	Poaceae	Poales	Commelinids	Moderate
Zea mays. Popcorn	ZEAmay.Pop	8	Poaceae	Poales	Commelinids	Moderate