IGNITION THRESHOLDS FOR GRASSLAND FUELS AND IMPLICATIONS FOR ACTIVITY CONTROLS ON PUBLIC CONSERVATION LAND IN CANTERBURY

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ii. Abstract

Grassland fuels quickly respond to moisture changes in the environment, and successfully ignite more readily compared with other wildland fuel types. In recent years in New Zealand grasslands, wildfire ignitions have increased due to recreational activities on public conservation land. Ignition sources have included off-road vehicles, sparks from machinery, and campfires, cooking stoves, etc. This research investigated ignition thresholds for fully cured tussock (*Festuca novae-zelandiae*) and exotic (*Agrostis capillaris*) grasses, with the aim of providing a scientific basis for wildfire prevention through decision-support tools for activity controls.

Five ignition sources of concern to the Department of Conservation were tested in the laboratory, and results were validated against field experiments. Experiments were innovative, and were designed to simulate ignitions from: hot exhaust systems on off-road vehicles (hot metal); sparks from vehicle exhausts (carbon emissions); grinding operations (metal sparks); smouldering debris dropped onto grass fuels from hot vehicle parts (organic embers); and ordinary cigarette lighters (open flame). Fuel moisture content (MC), and wind speed were varied, but ambient temperature and relative humidity were kept relatively constant in the laboratory.

Logistic regression was used to analyse data for each ignition source, except organic embers because no ignitions occurred. Ignition thresholds were determined for a probability of ignition success of 50%, and all models were statistically significant. The thresholds are listed in terms of model accuracy for each experiment: open flame was 28% MC without wind, and 55% MC with light wind (1 m/s); metal sparks was 37% MC; hot metal, with a wind speed of 2 m/s and MC of 1%, was 398ºC hot metal temperature; and carbon emissions was 65% MC.

The results represent a significant contribution to knowledge of the ignition behaviour of grassland fuels. Further research is required to verify and extend the results; but, initial findings provide a scientific basis for management, investigations of wildfire causes, and decisions around controls on recreational activities to protect highly sensitive ecosystems and natural areas from damaging wildfires.

iii. List of Figures

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v. List of Abbreviations

4WD - Four Wheel Drive

A - Answers

AFM - Accessory Fuel Moisture

AIC - Akaike Information Criterion

ATV - All Terrain Vehicle

BP - Before Present

BUI - Build-up Index

CFFDRS - Canadian Forest Fire Danger Rating System

CPLA - Crown Pastoral Land Act

DC - Drought Code

DMC - Duff Moisture Code

DOC - Department of Conservation

DPF - Diesel Particulate Filter

FBP - Fire Behaviour Prediction

FFMC - Fine Fuel Moisture Code

FI - Flaming Ignition

FOP - Fire Occurance Prediction

FWI - Fire Weather Index

GI - Glowing Ignition

ISI - Initial Spread Index

ISO - International Organisation for Standardisation

LINZ - Land Information New Zealand

LST - Local Standard Time

MC - Moisture Content

NI – No Ignition

NRFA - National Rural Fire Authority

NZFDRS - New Zealand Fire Danger Rating System

NZFS - New Zealand Fire Service

NZFSC - New Zealand Fire Service Commission

Q - Questions

RH - Relative Humidity

s.e. - standard error

SIV - Significant Inherent Value

TAGB - Total Above-Ground Biomass

UTE - Utility Vehicle

Chapter 1. Background

1.1 Introduction

Wildfires are a major concern to society throughout the world. New Zealand is no exception, with climatic conditions conducive to fires, and extensive wilderness areas. Fire researchers and managers strive to minimise wildfire risk in several ways. Decision-support tools, such as fire danger rating systems, incorporate models of fire behaviour and fuel flammability and are crucial to successful wildfire management. Other risk mitigation practices include use of fire history or experience, fire simulators, careful preparation for fire suppression activities, activity controls or restrictions, and public education. It is also important to investigate ignition causes after fires. In New Zealand, fire management of rural areas is the responsibility of a number of organisations, including the National Rural Fire Authority, the Department of Conservation (DOC), forestry companies, and local authorities. These organisations protect forests, scrublands, grasslands, and other rural areas from fire.

DOC manages the conservation of public land, including many grassland and wetland areas. Canterbury contains vast grassland areas, and DOC is particularly concerned about mitigating against wildfires in these areas. Canterbury’s hot, dry summers can result in extremely high levels of fire danger in grasslands, threatening wetlands and other vulnerable conservation areas. Therefore, an accurate knowledge of ignition thresholds in grassland fuels, from various ignition sources, is essential in order to manage wildfire risk effectively.

This chapter provides background information on grasslands, fire history, conservation, and fire management in New Zealand. In addition, an overview of the New Zealand Fire Danger Rating System (NZFDRS) is included, with particular emphasis on its application in grasslands. The chapter concludes with a description of the study structure, objective, and research questions.

1.2 Grasslands, Wetlands, and Fire Influences

Throughout history, fire has played an important role in shaping different ecosystems in New Zealand. Unfortunately, post-human arrival, it can be difficult to determine whether historic fires were caused by natural events or human activity. The extent of grassland areas has increased dramatically due to frequent fires, including burning by land clearing, other activities, and natural events. This section presents an overview of present-day grassland and wetland classification in the South Island. It is followed by an account of how fire has contributed to the current distribution of grasslands. The section ends with a description of fire occurrence and extent in New Zealand, particularly in relation to grasslands.

1.2.1 Grassland and Wetland Classification in Canterbury and the South Island High Country

The South Island high country is located inland, and includes about 6.7 million ha of sparsely populated land and water, from high to low elevations (Department of Conservation, 2009a). Tussock grasslands support vegetation that frequently grows in place of original forest and shrubland; notwithstanding, grasslands exist naturally in some alpine areas. Grassland is the most dominant ecological landscape type of Canterbury's high country, a result of thousands of years of landscape modification by natural and human factors (Molloy *et al.*, 1963; Winterbourn *et al.*, 2008). In Canterbury, ecological areas subjected to little modification show the following pattern: montane zones are covered by forest, and with increasing altitude forest changes to shrubland, which then gives way to grassland. Above grassland, little vegetation is capable of growing and sometimes only bare rock or shingles exist, often covered in snow. Much of the eastern South Island high country shows a different pattern. Here, grasslands exist between 900 and 1300 m above sea level. Without much landscape modification, a native treeline would have been obvious at these elevations but instead, a gradual change in grassland type is observed. Generally, hard tussock (*Festuca novae-zelandiae*) is present below this transitional area, with snow tussock (*Chionochloa* spp.) abundant above. These grasses are classified as short and tall tussocks respectively.

Table 1.1 Ecological zones in Canterbury classified by elevation (adopted from Winterbourn *et al.*, 2008)

Zone	**Elevation (m)**
Nival	≥ 2150
High Alpine	1850 - 2150
Low Alpine	1300 - 1850
Subalpine	900 - 1300
Montane (upper cool-temperate)	200 - 900
Lowland (lower cool-temperate)	0 - 200

To understand present-day grassland classification, it is useful to review how indigenous vegetation is classified into different zones, characterised by elevation (Table 1.1). The montane zone supports simple forest types dominated by mountain totara (*Podocarpus hallii*) and mountain toatoa (*Phyllocladus alpinus*), or beech (*Nothofagus*) tree species (Winterbourn *et al.*, 2008). These forests are less species-rich compared with lowland forests, which exhibit a highly complex structure. Only about 1000 ha of lowland forest remains intact in Canterbury, near the base of high country slopes. Remnants are found near Mt. Peel, extending into the lower Rangitata Valley, Mt. Hutt, the Rakaia Gorge and lower Rakaia Valley, and in several other places along the foothills (Winterbourn *et al.*, 2008). Stands are dominated by kahikatea (*Dacrycarpus dacrydioides*), totara (*Podocarpus totara*), and matai

(*Prumnopitys taxifolia*). At least 12 species of broadleaf trees are also present, alongside many shrubs, ferns, and other plants. The subalpine zone is a transition area from forest to shrubland. The alpine zone is divided into two subzones: 1) low alpine with tall grasses and some shrubs, and 2) high alpine with shorter grasses, cushion plants, and barren stonefields with scattered plants. Above 2150 m, the nival zone supports very little or no plant life. Grasslands that occupy these different zones support numerous plant-types depending on elevation, soil characteristics, and climate.

Tussock grasses are the dominant species present in South Island grasslands. Broad-leaved herbs, dwarf shrubs, and other grass species can be found interspersed amongst tussocks. Grassland ecosystems provide habitat for many life forms and facilitate important symbiotic relationships. For example, some high country grasses flower and set seed every three to five years, providing a seed source for insect larvae. They depend on each other in order to flourish. In the Canterbury high country, grasslands are categorised into three broad types: low-level and montane short grasslands, montane and subalpine tall grasslands, and alpine tall and short grasslands (Winterbourn *et al.*, 2008). Table 1.2 contains a list of the plants found in each category. Plant-types vary depending on site location and type.

Tussock grasslands are characterised by land, dominated by grass species, and usually do not contain trees or large shrubs. Native grass species are usually interspersed with exotic grasses. Tussock species are perennial, grow in a tuft that spreads outward like a fan, and have smooth blades. New Zealand native tussocks belong to three genera, *Chionochloa*, *Festuca*, and *Poa*. Tall tussocks, up to 1.5 m tall, include *Chionochloa* spp., whereas short tussocks, less than 50 cm tall, include *Poa cita* and *Festuca novae-zelandiae* grasses. Tussock grass generally has a build-up of cured grass at its base, and exotic does not. Exotics are shorter than tussocks, exhibit a rougher texture, and have fine inflorescence at the top 15 to 20 cm of their stems. Common exotic species include browntop (*Agrostis capillaris),* and sweet vernal (*Anthoxanthum odoratum).*

Table 1.2 Grassland classification in the South Island (adopted from Winterbourn *et al.*, 2008).

Grassland Type	Site Location	Site Type	Dominant Grass Species	Associated Grass, Herb and Dwarf Shrub Species	Most Common Foreign Grasses
Low-level and montane short grasslands	low to mid-slopes on eastern foothills	relatively fertile	*Poa cita* (silver tussock)	*Carex breviculmis* *Coprosma petriei* (a sedge) *Leucopogon fraseri* *Dichondra repens* *Elymus solandri* (a grass) *Geranium sessiliflorum* *Helichrysum filicaule*	*Hieracium pilosella* *Agrostis capillaris* *Anthoxanthum odoratum* *Festuca rubra* *Holcus Lanatus*
		less fertile, harder sites	*Festuca novae-zelandiae* (hard tussock)		
	areas within mountains on valley floors, basins and lower hill slopes up to 1300 m	well-drained	*Festuca novae-zelandiae* (hard tussock)	As above, plus: *Brachyscome sinclairii* *Plantago spathulata* *Raoulia subsericea* *Scleranthus uniflorus* *Poa colensoi* (a grass)	
	Mackenzie Basin	very dry	*Festuca novae-zelandiae* (hard tussock)	As above, plus: *R. beauverdii* *R. parkii* *Hebe pimeleoides* *Rytidosperma pumilum* (may be present, a grass)	
	Rakaia Valley northward (valley floors, basins and lower hill slopes up to 1300 m)	well-drained	*Festuca novae-zelandiae* (hard tussock)	As above, plus: *Pimelea serceovillosa* however *R. beauverdii* is NOT present	
	valley floors, basins and lower hill slopes up to 1300 m further west in the mountains	moist	*Festuca novae-zelandiae* (hard tussock)	*Gentianella serotina* *Coprosoma stropurpurea* *Gaultheria parvula*	

Table 1.2 Grassland classification in the South Island (adopted from Winterbourn *et al*., 2008), cont.

Grassland Type	Site Location	Site Type	Dominant Grass Species	Associated Grass, Herb and Dwarf Shrub Species
Montane and subalpine tall grasslands	montane parts of South and mid-Canterbury	well-drained to moist	*Chionochloa* spp. (tall tussocks or snow grasses)	
	wetlands	waterlogged	*C. rubra* (red tussock)	
	subalpine and upper montane	well-drained to moist	*C. rigida* (narrow-leaved snow tussock) *C. flavescens* (broad-leaved snow tussock)	*Celmisia spectabilis, Acaena caesiiglauca, Aciphylla aurea, Brachyglottis bellidioides, Elymus solandri, Festuca novae-zelandiae, Gaultheria depressa, Geranium sessiliflorum, Anaphalioides bellidioides, Kelleria dieffenbachii, Leucopogon fraseri, Luzula rufa, Pimelea oreophila, Poa colensoi, Viola cunnungchamii,* and *Wahlenbergia albomarginata* Often, the following are also present: *Coprosma, Hebe and Discaria spp., Leucopogon colensoi, Pentachondra pumila, Blechnum pennamarina,* and *Lycopodium fastigiatum*
	western mountains above the treeline and/or rocky valley-head slopes, old moraines, and margins of avalanche chutes	various	*C. flavescens* (broad-leaved snow tussock)	*Coprosoma pseudociliata, C. serrulata, Hebe subalpina, H. macrantha, Aciphylla scott-thomsonii, Anisotome haastii, Celmisia armstrongii, Dolichoglottis scorzoneroidies, Ourisia macrocarpa, Phormium cookainum,* and *Ranunculus lyallii*
	severe avalanche chutes	various	*Poa cockayneana* (avalanche grass) or sometimes *P.colensoi* or *P.hesperia*	
	higher mountain valleys on young river terraces	various	*Festuca matthewsii* (a smaller blueish tussock)	
Alpine tall and short grasslands	inner eastern and higher foothill ranges on higher slopes	various	*Chionochloa macra* (slim snow tussock)	Most of the same plants accompanying *C. rigida* and *C. flavescens* plus: *Celmisia lyallii, C. spectabilis* var. *spectabilis, C. viscosa, C. densiflora, C. angustifolia, C. sessiliflora, Podocarpus nivalis, Coprosma cheesmanii,* and *Hebe pinguifolia*
	westerly mountains	young stony, relatively fertile	*C. pallens* (midribbed snow tussock)	Some of the plants above are also found here, plus: *Poa colensoi, P. hesperia, Astelia linearis, Coprosma perpusilla, Euphrasia revoluta, Forstera sedifolia, Gentianella montana, Oreobolus impar,* and *Uncinia divaricata*
	westerly mountains	waterlogged, less fertile	*C. crassiuscula* (curly grass)	
	mountains from the northern tributaries of the Waimakariri and the Puketeraki Range north of Mt. Terako (east) to the Spenser Range and beyond (west)	deep snow cover	*C. australis* (carpet grass)	

Table 1.3 Wetland classification in the South Island (adopted from Winterbourn *et al.*, 2008).

Wetland Type	**Site Location**	**Site Type**	**Common Plant Species**	
Marsh, turf vegetation and swamps associated with lakes	throughout Canterbury next to lakes	marshes (fertile water)	*Schoenus pauciflorus* (red sedge) *Carex sinclaririi* *C. coriacea*	*C. virgata* *Myriophyllum spp.*
	Mackenzie Basin lakes, lagoons around smaller lakes, and tarns	turf areas	*Crassula sinclairii* *Galium perpusillum* *Glossostigma* spp. *Euchiton* spp. *Isolepis* spp.	*Leptinella maniototo* *Liaeopsis ruthiana* *Limosella spp.* *Neopaxia leariifolia* Plus many more
	swamps	floors of lakes or permanent water bodies	*Typha orientalis* (raupo) *Phormium* spp. (harakeke) *Carex secta* (tussock sedge)	*Cortaderia richardii* (toetoe)
Valley-floor marshes and tall grassland	near lakes, and in valley floors next to streams	waterlogged by underground seepage	*Chionochloa rubra* *Schoenus pauciflorus* (red sedge) *Carex* spp. *Viola cunninghamii* *Anisotome aromatica*	*Olearia bullata* *Bulbinella angustifolia* (golden-flowered swamp lily, or Maori onion) *Herpolirion novae zelandiae* *Marzus*
Streamside and hillslope flushes	streams high on the mountain slopes	fertile, with well-aerated water	*Epilobium macropus* *Montia fontana*	*Poa dipsacea* *Psychrophila novaezelandiae*
	seepage flushes, with water spreading widely down a slope	fertile	*Schoenus pauciflorus* (red sedge) *Marsippospermum gracile* may be dominant on upper-level flushes	
	waterfalls	fertile	As above, plus: *Dolichoglottis lyallii*	*Ourisia macrophylla* *Craspedia* spp.
	small streams	fertile	*Schoenus pauciflorus* (red sedge) *Rumex flexuosus*	*Gunnera dentata* *Ranunculus maculatus*
Bogs	valley bogs at locations such as Lake Tennyson, Waiau, Hurunui, Waimakariri Valley, and most sites surrounded by beech forest	infertile, acidic	*Sphagnum cristatum* *Gleichenia dicarpa* *Empodisma minus* *Schoenus pauciflourus*	*Chionochloa rubra* bog pine *Dracophyllum palustre* *Hebe odora* inaka
	cushion bogs usually close to the Main Divide on passes and terraces	infertile, acidic	*Donatia novae-zelandiae* *Phyllachne colensoi* *Oreobolus pectinatus* *Cythaodes pumila* *Gentianella bellidifolia*	*Drosera arcturi* *D. spathulata* *Utricularia monanthose* *Sphagnum falcatulum* *Haloca* spp.
	small cushion bogs among red tussock areas on the summit of Mt. Somers, on ancient moraines in the eastern Arrowsmith Range, and on the flanks of the Two Thumb Range	infertile, acidic	*Oreobolus pectinatus* *Abrotanella caespitosa* *Carpha alpina* *Carex echinata* *C. gaudichaudiana*	*Coprosma perpusilla* *Schoenus* *Sphagnum cristatum*

Wetlands are commonly found amid grassland ecosystems. Many unique plants and vegetation types occupy wetlands, and are characterised by adaptations that help them flourish in anaerobic or waterlogged conditions (without oxygen). They grow to various sizes and heights, but usually do not exceed two metres tall. A classification of wetland plant communities is summarised in Table 1.3. There are four broad wetland types: marsh, turf vegetation and swamps associated with lakes; valley-floor marshes and tall grassland; streamside and hillslope flushes; and bogs. Wetlands can support endangered plants and animals and need to be protected from threats such as pests and fire, unless fire is a natural or integral part of the wetland.

Over thousands of years, natural and human influences have caused tussock grasslands to form. They are now considered to be a natural vegetation cover class and are maintained by fire and grazing (Ogden *et al.*, 1998; McGlone, 2001). When tussocks die, the leaf bases and sheaths dry out, causing them to be highly flammable. Wetlands can also dry out and usually contain enough vegetation to ignite fires. Frequent drought, fine grassland vegetation, and foehn winds (in certain locations), can all predispose these ecological areas to frequent fire (Ogden *et al.*, 1998). In order to prevent future loss of grasslands and wetlands, DOC is managing them with the goal of protection in mind. Grasslands and wetlands are also highly regarded for their economic, visual, and recreation values (McGlone, 2001).

1.2.2 Fire History and South Island Grasslands

Most indigenous flora and fauna of New Zealand do not have adaptations to help them survive through, or flourish after fire (Ogden *et al.*, 1998). However, charcoal analysis and fire history indicates that fire was a regular occurrence in drier areas of New Zealand. There were six or more fire periods between 2000 and 6500 BP, as indicated by high charcoal deposits found in soil (McGlone, 1989). In the South Island, lightning was responsible for most natural fires, and volcanic eruptions were another natural source (Molloy *et al.*, 1963; McGlone, 1989; Ogden *et al.*, 1998; Guild & Dudfield, 2009). After fire, tussock grass was usually the first vegetation type to re-establish.

Analysis of historic New Zealand vegetation indicates that forest covered 85-90% of land area in 3000 BP. Grassland was naturally present on flood-prone river terraces, cold valleys, cliff edges, sand dunes, poor and ultramafic soils, and disturbed forest areas. On the South Island western mountain ranges, *Chionochloa* spp. existed above the treeline, and in the dry interior, a mix of grass and shrubs was present. At lower elevations, other grass species were scattered throughout forest areas (Connor, 1964; McGlone, 2001). New Zealand weather records indicate that since 3000 BP, there has been a trend towards increased precipitation and stronger winds. McGlone (1989) suggests that these weather changes caused the landscape to begin changing to scrubland and grassland before Polynesians arrived.

It is impossible to distinguish between natural and human-caused fires that occurred many years ago. However, if 1000 BP is accepted as the date of human settlement, several trends can be reported (McGlone, 1989). Charcoal deposits, dated and organised into common age categories, provide an idea of fire history. Ogden *et al*. (1998) defined 'fire interval' as 'the average time between sequentially dated charcoal samples'. Shorter intervals imply that fires occurred more frequently. From about 10,000 to 3000 BP, fires occurred in intervals of about 200 years. After 3000 BP, fire frequency increased fourfold to intervals of about 50 years. This corresponds to an increase in naturally caused fires. Fire intervals shortened to approximately a decade between 700 and 500 BP, when fires occurred most frequently. This was probably when Maori increased fire-use. Further fire activity corresponds with European settlement between 240 and 60 BP. 'Fire interval' analysis provides an idea of fire frequency, but pollen analysis combined with charcoal analysis provides an indication of how fire-use modified the landscape.

The presence of charcoal indicates that a fire occurred, whereas pollen analysis reveals evidence of new grasslands in place of indigenous forest. Pollen analysis is the primary method used to determine grassland history (McGlone, 2001). When grasses decay, they leave behind microfossil phytoliths and pollen. Phytoliths can also be analysed, but the method is not used as frequently. At the family level, the difference between pollen characteristics is obvious, but separating pollen into genera is more difficult (McGlone, 2001). A large increase in charcoal deposits, alongside a decrease in tree and shrub pollen, and an increase in grass-type pollen, indicates that fire has caused grassland to replace forest. Such events were identified between 800 and 400 BP (McGlone, 1989; Ogden *et al.*, 1998; McGlone, 2001; Winterbourn *et al.*, 2008). Pollen analyses agree with charcoal analyses, suggesting that Polynesian fire-use was at its peak at that time. Furthermore, podzol soil-types generally only form under forest cover, such as mountain beech, but they can still be found under present-day tussock grassland (Molloy *et al.*, 1963).

Polynesian settlers used fire for two main reasons: land clearing and moa hunting. Burning initially took place in dry, fertile lowlands, on the eastern South Island coast. Montane areas were then cleared to create access to the interior and further south. Consequently, almost all indigenous forest was destroyed in these areas (Newsome, 1987; McGlone, 1989; Ogden *et al.*, 1998). Moa hunting was widespread from 1000 to 500 BP. Fire facilitated hunting and destroyed moa habitat near the coast or in lowlands. Following fire, non-*Chionochloa* spp. dominated as primary succession species in drier areas due to their high reproduction rates, good dispersal, and fast growth rates. They included *Poa*, *Festuca*, *Rytidosperma*, and *Elymus* spp. Wetter sites became dominated by slow-growing *Chionochloa* spp. (Ogden *et al.*, 1998). Polynesians made a considerable impact on native forest, facilitating the creation of new grasslands. This impact became more severe when Europeans arrived in the 1800s.

By the 1840s, forest cover had declined to about 45% of New Zealand's land area (McGlone, 1989). By this stage, tussock grasslands containing *Chionochloa rubra*, *C. rigida*, and *C. marca* were present in place of many indigenous forests (McGlone, 2001). Throughout the 1850s and 1860s, European settlement continued to influence the landscape. Fire-use persisted, as farming, logging, and exploration activities intensified. Records suggest that accidental fires became widespread (Winterbourn *et al.*, 2008). As grasslands were transformed into farmland, fire was used to clear unwanted vegetation, to increase the growth of new palatable grass shoots, and to prepare land for seeding of European grasses. These management practices made stock handling easier, thus facilitating sheep farming (Newsome, 1987; Winterbourn *et al.*, 2008). Logging in places such as Waimate, Geraldine, Mt. Somers, Oxford, and Waiau resulted in fires that further destroyed forest land. These practices continued throughout the 19th and 20th centuries (Winterbourn *et al.*, 2008).

By 1910, forest destruction slowed, but did not end. It was not until the 1950s that almost all lowland areas were void of forest and scrub, and replaced by agriculture. Every couple of years during the 1950s and 1960s, farmers burned tussock grassland in late spring or early winter to encourage new shoot growth. In the 1970s, many grasslands were converted to cropland due to the wheat production boom (Newsome, 1987). At this time, browntop (*Agrostis capillaris*) was the most dominant exotic grass throughout tussock grasslands. It negatively affected plant diversity throughout grasslands, and by 1990 it covered about 99% of inter-tussock areas (Winterbourn *et al.*, 2008). Grazing by introduced mammals added to the adverse change within these ecosystems.

Fire may not transform tussock grasslands into new communities with different dominant species on its own (Winterbourn *et al.*, 2008). Burning combined with heavy grazing causes tall tussocks to die out, and prevents forest cover from returning. Throughout history, fire has caused mass forest destruction, creation of tussock grassland, and extensive conversion of tall tussock grassland to short tussock (Connor, 1964; 1965; Winterbourn *et al.*, 2008). For example, in the montane zone, management practices have caused snow tussock and red tussock to be replaced by fescue tussock. Erosion has become a problem in some places, where tussock numbers have been reduced due to excessively high burning rates (Newsome, 1987). It is becoming increasingly important to protect tussock grassland in sensitive ecosystems and public conservation land.

Fire-use can be regarded negatively from a conservation point of view; however, it can be used as a beneficial management practice. Depending on the situation, tussock burning can be used for the following:

a) removing litter and old tussock/intertussock grass to promote faster new grass growth;
b) reducing the number of tussock grasses to give stock more grazing room;
c) controlling weeds and slowing shrub growth;
d) reducing litter build-up to reduce fire risk from different ignition sources; and
e) preparing land for activities such as over sowing, topdressing, or afforestation (Parliamentary Commissioner for the Environment, 1995).

In the Canterbury high country, tussock grassland burning is a permitted activity in many cases. A set of criteria must be met if the land manager wishes to burn, otherwise resource consent is required (Environment Canterbury, 2009). Burning is only permitted if it is ecologically sustainable. In spring, fires pose little threat to the ecosystem because fuel moisture content is high; however, if they are lit under hot, dry conditions they can destroy tussocks and decrease plant biomass and soil nutrients (Payton & Pearce, 2009). Regardless of the benefits of fire-use as a management tool, farmers and other land managers are required to consider the long-term sustainability of the land before burning tussock grasslands.

1.2.3 Wildfire Events in New Zealand

In New Zealand, the most comprehensive study of past wildfire events was recently completed by Doherty *et al.* (2008). The study included data from 1991 to 2007, which was obtained from the National Rural Fire Authority's (NRFA) database of wildfire records. Main findings indicated that each year an average of 5,865 ha was burned, with an average of 3,033 wildfires. Moreover, there was a trend of increasing wildfire numbers over this period. Study results suggest that 18.2 percent of New Zealand's wildfires occurred in Canterbury, the highest of all regions. Grass fires accounted for the highest proportion of the annual area burned nationally at 53.7% (3150.2 ha), compared with scrub and forest fires (39.7 and 6.6% respectively). Table 1.4 details the average annual fire area and proportion by region and fuel type. Canterbury recorded an average of 342.6 ha of grassland burned per year, making it the region with the third largest annual area burned. Otago had the largest area burned (1781.0 ha), followed by Nelson/Marlborough (491.2 ha).

Table 1.4 Average annual area burned from 1991 – 2007, displayed by fuel type and region (adopted from Doherty *et al.*, 2008).

Region	Grass Area (ha)	Grass Area Proportion (%)	Scrub Area (ha)	Scrub Area Proportion (%)	Forest Area (ha)	Forest Area Proportion (%)	Total Area (ha)	Total Area Proportion (%)
Northland	53.4	1.7	339.5	14.6	46.6	12.1	439.5	7.5
Auckland	20.4	0.6	35.1	1.5	1.5	0.4	57.0	1.0
Waikato	22.5	0.7	39.3	1.7	2.4	0.6	64.2	1.1
Wanganui/Manawatu	48.8	1.5	70.4	3.0	11.7	3.0	130.9	2.2
Central North Island	20.8	0.7	86.2	3.7	29.1	7.5	136.1	2.3
Taranaki	5.5	0.2	16.1	0.7	8.4	2.2	30.0	0.5
Eastern North Island	171.4	5.4	198.5	8.5	76.2	19.7	446.0	7.7
Greater Wellington	27.2	0.9	90.4	3.9	20.7	5.4	136.7	2.4
Nelson/Marlborough	491.2	15.6	147.6	6.3	83.2	21.6	722.0	12.4
West Coast	32.9	1.0	205.9	8.8	10.1	2.6	248.9	4.3
Canterbury	**342.6**	**10.9**	**285.6**	**12.3**	**40.0**	**10.4**	**668.2**	**11.5**
Otago	1781.0	56.5	631.1	27.1	47.3	12.3	2459.3	41.5
Southland	132.5	4.3	184.8	7.9	8.6	2.2	325.9	5.6
Total	3150.2	100.0	2330.5	100.0	685.6	100.0	5824.9	100.0

Table 1.5 Proportion of total wildfires and grass wildfires by cause from 1991 – 2007 (adopted from Doherty *et al.*, 2008).

Wildfire Cause Category	List of Causes Included in Each Category	Proportion of Total Number of Wildfires (%)	Proportion of Total Grass Area Burned by Wildfires (%)
Miscellaneous	Carelessness (smokers and chainsaw users etc.), Children, Electrical Faults, Other	33.1	3.5
Land Clearing	Burnoffs, Rubbish, Unpermitted Burns	20.1	53.0
Vehicles	Lawnmowers, Road Traffic, Tractors and Motor Vehicles	16.5	5.1
Unknown	Scrub Fires and Vegetation Fires	13.4	28.1
Incendiary	Army and Fireworks	5.8	2.0
Recreational	Hunters, Picnics, Camping	3.3	1.0
Structures	Barns, Hay Barns, Houses	2.2	0.0
Industrial	Industrial/Structures, Super Skid	1.8	0.7
Railways	Tramways	1.6	2.4
Smokers	Cigarettes	1.0	0.2
Arson	Vehicle Arson	0.7	0.1
Power Lines	Power Lines	0.2	3.8
Lightning	Lightning	0.1	0.1
Chainsaw	Chainsaw	0.1	0.1

The main causes of wildfires across New Zealand are summarised in Table 1.5. Because the NRFA does not keep a consistent record of causes, some causes are listed in multiple categories. Of all grass areas burned in New Zealand, over 50% of fires were caused by land clearing activities, followed by approximately 28% from unknown sources. Vehicles, power lines, railways and other miscellaneous sources also caused grass fires and should be regarded as significant ignition risks. The study clearly identifies that nearly all wildfires in New Zealand are the result of human causes. Therefore, fire management should focus more on preventive management so that fire is mitigated against before it starts, rather than relying on reactive measures that are implemented after fires start.

Another relevant study assessed wildfire causes in Canterbury from 1997 to May 2007, using data obtained from the Department of Conservation database (McEwan, 2007). 0 summarises grass-fire causes for Canterbury. Most grass fires were caused by unknown sources (33%), followed by unauthorised burn breakaways (13%). Other significant causes were railways (11%), recreation/hunters/campfires (10%), arson/incendiary (9%), motor vehicles (8%), and authorised burn breakaways (6%). These ignition sources are comparable to those reported by the NRFA. McEwan (2007) also reports that grassland fuels are more likely to burn when fire danger is low, compared with scrub and forest fuel-types.

Table 1.6 Proportion of total grass fires in Canterbury by cause from 1997 – May 2007 (adopted from McEwan, 2007).

Wildfire Cause	**Proportion of Total Grass Area Burned by Wildfires (%)**
Unknown	33
Burn Breakaway - unauthorised	13
Railways	11
Recreation/hunters/campfires	10
Arson/Incendiary	9
Motor Vehicles	8
Burn Breakaway - authorised	6
Smoking/Matches	3
Tractors/Other Machinery	3
Burn Breakaway - unspecified	1
Lightning	1
Power Lines	1
Rubbish Fires	1

1.3 Department of Conservation (DOC)

In 1987, the Conservation Act rendered the conservation of New Zealand's heritage the responsibility of DOC (Department of Conservation, 2008b). In Māori, DOC is referred to as *Te Papa Atawhai,* which is analogous to a box or container that cares, nurtures, or preserves treasures (Department of Conservation, 2009a). DOC is New Zealand's central government organisation responsible for protecting over 4.7 million hectares of land and water. Its mission is "to conserve New Zealand's natural and historic heritage for all to enjoy now and in the future" (Department of Conservation, 2009a). Recreation management is an important aspect of DOC's role, alongside goals to protect all types of indigenous wildlife and habitat.

DOC's structure relies on line management accompanied by service and support roles. Figure 1.1 shows how each hierarchical level is connected with strategic, improvement, sustainable, and delivery management roles. The head office is located in Wellington and features a Research and Development Group. There are two regional offices for Northern and Southern Operations. They are located in Hamilton and Christchurch respectively. The rest of DOC is separated into 13 conservancies, or regions throughout New Zealand (Department of Conservation, 2009a).

1.3.1 Canterbury Region

The Canterbury conservancy includes approximately 808,000 ha of public conservation land and extends into very remote areas (Department of Conservation, 2009a). The conservancy is further divided into five areas: Mahaanui, Aoraki, Raukapuka, Twizel, and Waimakariri (Figure 1.2). New recreation parks, with better public access, present an increased need to protect sensitive wetlands and catchments from fire, particularly in the Raukapuka area of Canterbury. This area includes land and water between the Rakaia and Waitaki rivers. It stretches from the east coast to the Hunter Hills and Burkes Pass, and south from the Two Thumb Range to the main divide of the Southern Alps. Main management concentrations for this area are biodiversity, habitat restoration, recreation, pest control, and community involvement (Department of Conservation, 2009a).

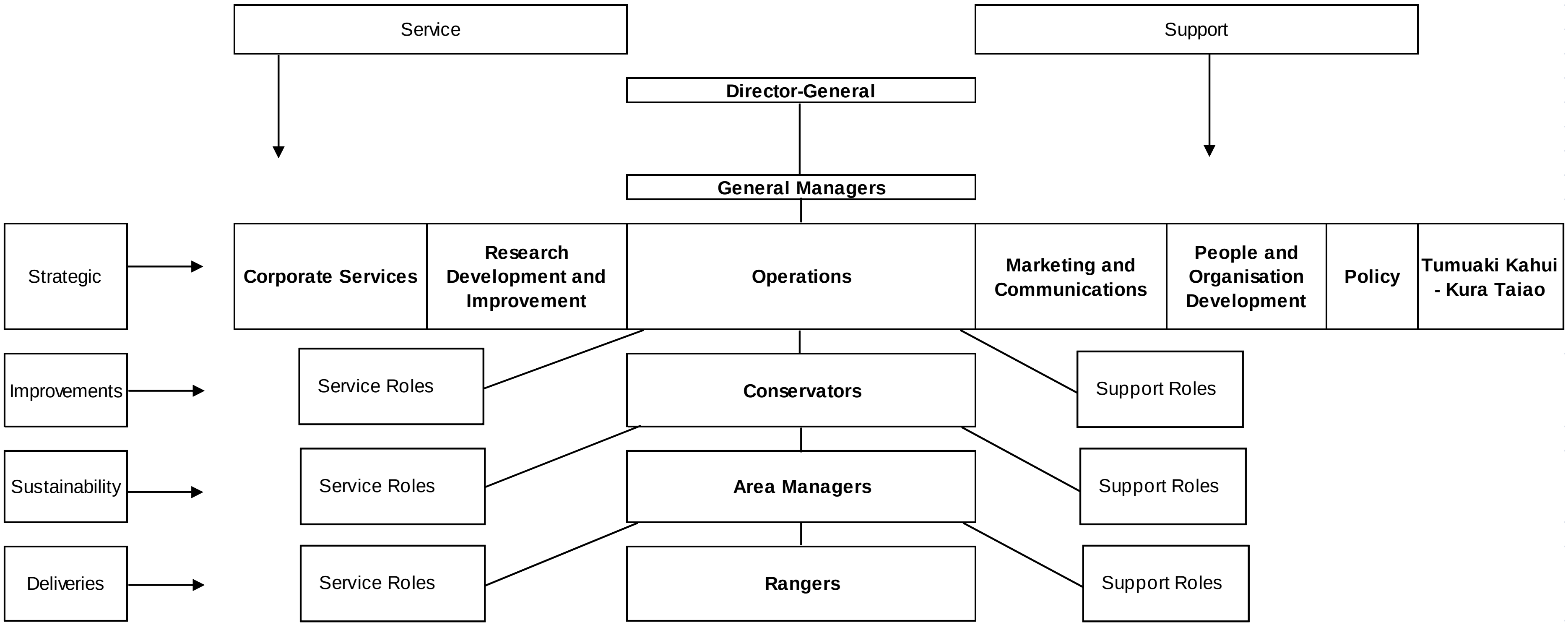

Figure 1.1 The structure of DOC (adopted from Department of Conservation, 2008b; 2009c).

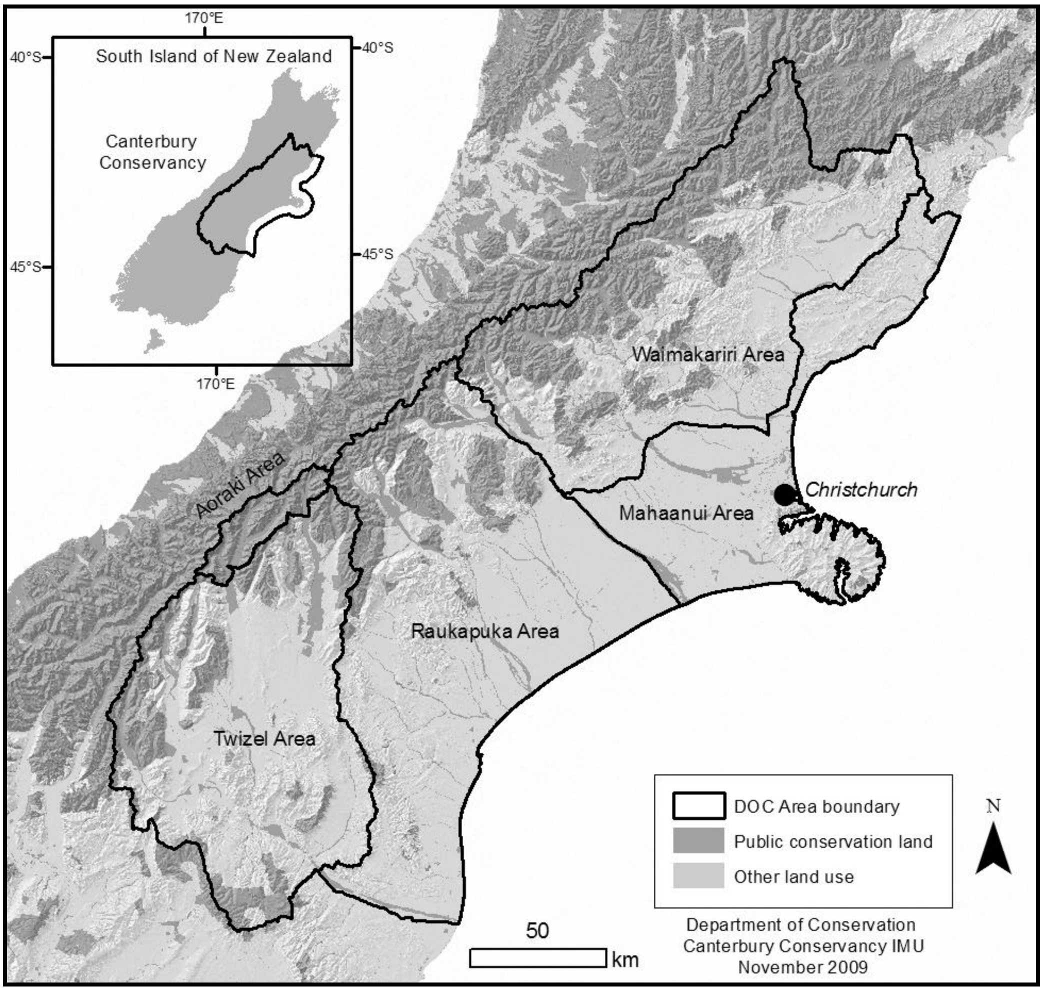

Figure 1.2 Canterbury conservancy showing DOC areas and public conservation land.

In October 2007, DOC opened the Hakatere Conservation Park within the Raukapuka area. It is located in the Ashburton Lakes basin between the Rakaia and Rangitata rivers. Since the park's opening, land tenure reviews have caused its size to grow from 60,000 to over 68,000 hectares of public conservation land (Department of Conservation, 2008d; Parliamentary Commissioner for the Environment, 2009). This, alongside the park's numerous recreational options, may cause it to become New Zealand's largest conservation park (Department of Conservation, 2008d; 2009b). Over 50 percent of the park is covered by intensive management areas of the Ō Tū Wharekai wetland. Moreover, this high country area features tussock grasslands above 500 m in flat locations, and down to 300 m in valleys (Parliamentary Commissioner for the Environment, 1995). It also includes mountains, rivers, lakes, and beech forest remnants. As park-users increase, conservation management becomes increasingly important so that sensitive areas remain protected.

1.3.2 Land Tenure Review

The South Island high country holds exceptional value to New Zealanders for its beautiful landscape, cultural importance, history, biodiversity, and recreational opportunities (Department of Conservation, 2009a; Parliamentary Commissioner for the Environment, 2009). Ngāi Tahu (Māori of the South Island) have spiritual and cultural connections with the land. High country farmers have been the focus of the 'Southern Man' icon, a tough and independent pastoral dweller, often depicted in New Zealand commercials. Artists, writers, outdoor enthusiasts, and tourists also value this landscape. Unfortunately, high country farming is currently facing an economic downturn. This is one of the many and varied motivations for entering into land tenure review.

There is a mixture of land tenures throughout the South Island high country, which includes pastoral leases. The tenure of a pastoral lease can be reviewed under a process called tenure review, which is carried out under the Crown Pastoral Land Act 1998 (CPLA). Land Information New Zealand (LINZ) administers the process. The decision to enter tenure review is voluntary, and the process was initiated in 1990. When the process is complete, more productive land is returned to the lessee under freehold status, and land with significant inherent values (SIVs) is returned to the Crown to be managed by DOC (Land Information New Zealand, 2004; Armstrong *et al.*, 2007; Parliamentary Commissioner for the Environment, 2009; Wilkins, personal communication, August 26, 2009). One objective of the CPLA is to protect SIVs. SIVs include land that has historic or cultural significance, unique ecological, recreational or scientific attributes, indigenous species, and/or considerable biodiversity (Department of Conservation, 2009a). Land is also considered to have SIVs if it contributes to ecosystem services. These services include environmental goods that are created by interactions between living things, such as air, water and soil that benefit humans. The tenure review process involves the pastoral leaseholder, DOC, Fish and Game, iwi, and the public. DOC is LINZ's main advisor for the tenure review process.

Pastoral leases give the leaseholder rights to graze the land; however, high country land contains sensitive ecosystems, so farmers are required to practise due diligence on the land, and LINZ reserves the right to control stock numbers. Farmer responsibilities include minimising waste, controlling plant and animal pests, and gaining consent for any activity that disturbs the soil, including fire-use. Throughout the 20th century, the legislation of pastoral land-use evolved to its current state (Table 1.7). Since 1990, tenure review has caused pastoral lease numbers in the South Island high country to drop from 304 to 107 (Table 1.8). This has caused a sevenfold decrease in pastoral lease area, from 2.16 million ha to less than 0.86 million ha.

Table 1.7 History of the administration of pastoral land-use (adopted from Armstrong *et al.*, 2007).

Time Period	Pastoral Land-Use Type	Administration	Particulars
1998 - present	Pastoral Lease	Crown Pastoral Land Act 1998	Annual rent is charged at 2.25 % of the land value (exclusive of land improvements) and is reassessed every 11 years. Perpetual renewal under a 33 year term.
1948-1998	Pastoral Lease	Land Act 1948	Rent was not a fixed rate, but the Land Settlement Board was required to fix a fair annual rent. Perpetual renewal under a 33 year term.
before 1948	Pastoral Occupational License	Government initiative to increase pastoral farming	License given under grant scheme. Fixed term for 21 years.

Table 1.8 Pastoral lease information before tenure review and its current status (adopted from Armstrong *et al.*, 2007; Urlich, 2009).

Pastoral Lease Region	Pastoral Lease Number Before Tenure Review	Pastoral Lease Area Before Tenure Review (ha)	Status as of November 2009				
			Pastoral Lease Number	Pastoral Lease Area (ha)	New Freehold License Area After Tenure Review (ha)	New Conservation Area After Tenure Review (ha)	Number of Tenures Under Review
Canterbury	112	868,559	37	340,969	131,561	79,827	54
Westland	2	2,590	1	1,214	~	~	1
Nelson/ Marlborough	15	110,853	6	35,817	66,727	26,022	5
Otago	155	948,497	51	341,211	109,094	86,201	63
Southland	20	228,193	12	138,894	~	~	6
Total	**304**	**2,158,692**	**107**	**858,105**	**307,382**	**192,050**	**122**

As stated in the CPLA, the main objectives of tenure review are

(a) To —

(i) Promote the management of reviewable land in a way that is ecologically sustainable:

(ii) Subject to subparagraph (i), enable reviewable land capable of economic use to be freed from the management constraints (direct and indirect) resulting from its tenure under reviewable instrument; and

(b) To enable the protection of the significant inherent values of reviewable land —

(i) By the creation of protective mechanisms; or (preferably)

(ii) By the restoration of the land concerned to full Crown ownership and control; and

(c) Subject to paragraphs (a) and (b), to make easier —

(i) The securing of public access to and enjoyment of reviewable land; and

(ii) The freehold disposal of reviewable land (Crown Pastoral Land Act 1998, 2008).

There are four main stages of tenure review (Land Information New Zealand, 2004). First, ‘information gathering’ is initiated after LINZ accepts the lessee’s invitation into tenure review. Consultation with different groups begins. Second, ‘preliminary proposal’ occurs when the first cut is drafted, which shows where the land will be divided into conservation and freehold sections; and, the lessee agrees to advertise the proposal for public submissions. Third, ‘substantive proposal’ occurs when the second cut is drafted, including any input from public or iwi, and the lessee decides whether to accept the final proposal or not. Fourth, ‘implementation of substantive proposal’ is when the lessee gains freehold title to a portion of the land, and the rest is returned to the Crown. It can take up to four years for tenure review to be completed. Table 1.9 presents a summary of land activities that are permitted once tenure review is complete.

Tenure review is slowly creating a mosaic of land tenures throughout the high country. As of November 2009, about 192,050 ha of land had been transferred back to the Crown as a result of tenure review (Urlich, 2009). About 307,382 ha had been transferred to freehold title (Table 1.8). Other increases to Crown land include whole property purchases, surrendered pastoral occupational licences, land improvement agreements, and reclassified land. Overall, approximately 430,000 ha have been added to South Island public conservation land over the last 19 years. An updated figure for Canterbury/Marlborough indicates that as of August 2009, 270,270 ha of pastoral land had become public conservation land and is now administered by DOC (Wilkins, personal communication, August 26, 2009). This figure also includes whole property purchases by the Nature Heritage Fund or the Crown.

Table 1.9 Possible land activities on South Island high country depending on land title (adopted from Parliamentary Commissioner for the Environment, 2009).

Possible Land Activities	Land Title (Indication of Allowable Land Activities ✓ = yes, × = no)	
	Pastoral Leasehold	Freehold
Increasing cattle, deer, or even alpaca numbers	✓ with permission from the Commissioner of Crown Land (CCL)	✓
Land improvement by clearance, drainage, irrigation, or topdressing	✓ with permission from the CCL	✓
Increased tourism, i.e. Farmstays, horse riding, 4WD tours, hunting, or fishing	✓ with permission from the CCL	✓
Dairy farming	×	✓
Carbon sequestration and agro-forestry	×	✓
Cropping or viticulture	×	✓
Residential development (lifestyle blocks, holiday accommodation, hotel complexes)	×	✓
Commercial activities (rural services, and wind farms or other electricity generation)	×	✓
Private conservancy	×	✓
Reducing the land to woody weeds, Hieracium, or desert	×	✓

Ewans (2004) reviewed recent publications on the "effects of grazing cessation on the indigenous grasslands of the eastern South Island of New Zealand" (p. 8). This is important due to changing management practices in the high country as a result of tenure review. One trend indicated a beneficial result: there is an increased number of indigenous species on land that is no longer grazed, compared with land that is still grazed. Native vegetation recovery is slow in these areas, and depends on a number of variables; therefore, this trend is not always observed. Research tends to signify that if stock grazing and rabbits are removed, native vegetation is likely to recover in places where good seed sources are available (Ewans, 2004). Other trends suggest that fuel continuity is reverting from patchy to continuous, and that fuel loading is transforming from low to high (Ewans, 2004). These trends indicate that if a fire were to occur in these areas, it would be larger and require more resources to control. Regardless of management issues that arise from tenure review, the process results in several positive outcomes. It provides farmers with new options for their marginally economic leasehold land, it increases tussock grassland protection, and it allows the public to enjoy more recreational activities in the picturesque high country.

1.3.3 Ō Tū Wharekai Wetland Restoration Project

In 2007, the national Arawai Kakariki wetland restoration programme was initiated. The programme will help DOC develop national management practices and monitoring standards for the Natural Heritage Management System (Department of Conservation, 2009a). The objective is "to enhance the ecological restoration of three of New Zealand's foremost wetland/freshwater sites, encouraging strong community involvement and promoting research into wetland restoration techniques" (Department of Conservation, 2008d, p. 1). Ō Tū Wharekai is one of the three sites, with a vision that "the intrinsic values of one of the best, remaining high country freshwater wetland and braided river ecosystems are protected, enhanced and appreciated" (Department of Conservation, 2008d, p. 1). In order to meet the objective and vision, public access needs better management strategies, and ecological information needs to increase and be available to users.

The approximate location of the Ō Tū Wharekai wetland in relation to Christchurch is shown in Figure 1.3. A map of Ō Tū Wharekai (Figure 1.4) shows public conservation land, catchment influence area, and intensive management area (approximately E1440000^{o}, N5170000^{o}). The area includes 12 lakes and tarns that drain south into the Ashburton River, with Lake Heron draining north into the Rakaia catchment. Many significant habitats, plants, and animals are found in the area. Grasslands border the many wetlands on glacial moraine and alluvial deposits. Recreational activities include fishing (sport/pleasure), wind-surfing, boating, kayaking, swimming, walking/tramping, camping, picnicking, hunting, game-bird shooting, and off-roading (Department of Conservation, 2008c). The Ō Tū Wharekai wetland restoration project has nine objectives that aim to allow recreation and other land-use to take place while protecting sensitive areas from further loss (Table 1.10).

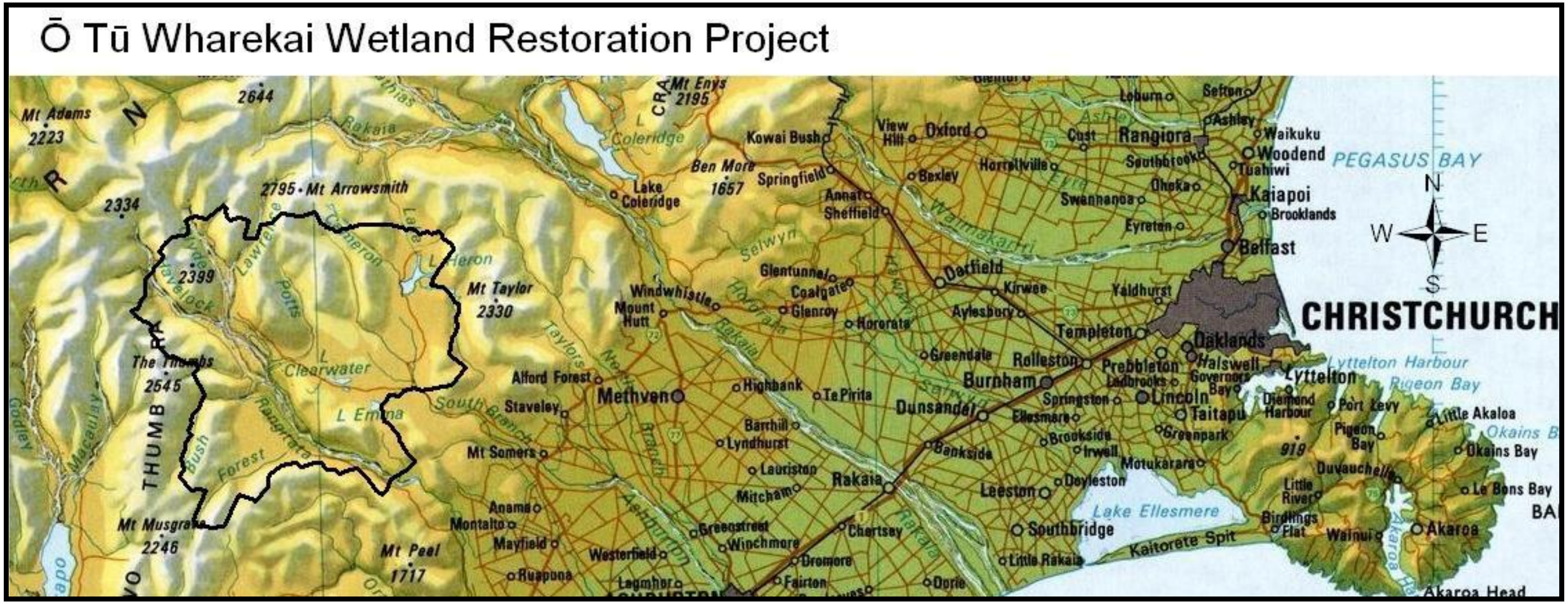

Figure 1.3 The approximate location of Ō Tū Wharekai (outlined in black) in relation to Christchurch (Integrated Mapping, 2009).

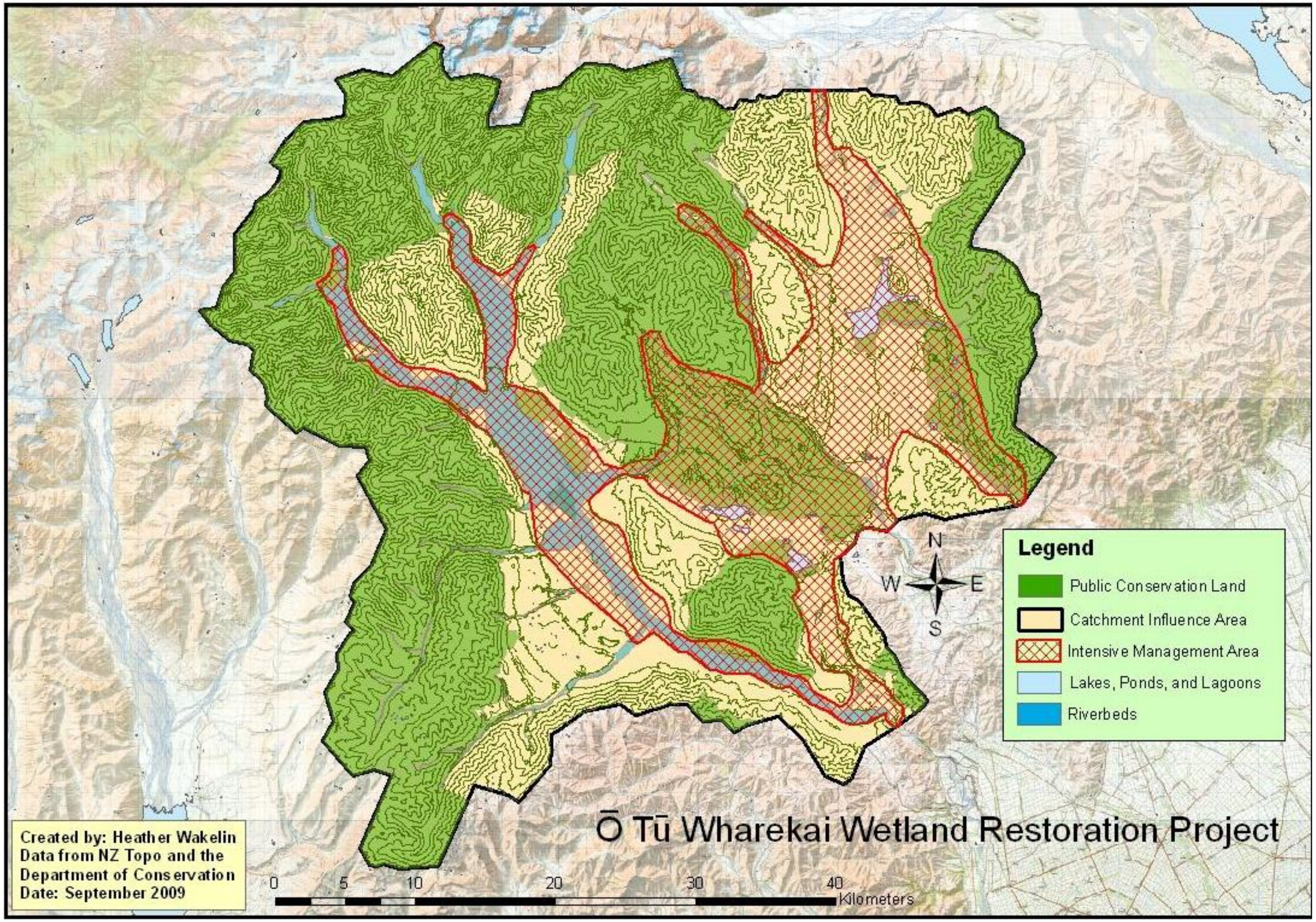

Figure 1.4 Map of the Ō Tū Wharekai Wetland Restoration Project showing different land types.

Table 1.10 Ō Tū Wharekai wetland restoration project objectives (adopted from Department of Conservation, 2008c; Lange, 2009).

	O Tu Wharekai Objective	Management Actions
1	Protect wetland area and prevent further loss	Advocate the project Mapping, classification, aerial photography analysis Restoration plantings at several sites Fence priority areas to protect from stock trampling and grazing Monitoring (surveying for inventory) Statutory processes: wetland protection, entering into the Resource Management Act, including in district plans, etc. **Fire control and risk mitigation**
2	Aim to preserve natural hydrological processes	Increase knowledge of water quantity and quality Research nutrient and sediment inputs Work with Environment Canterbury to monitor water quality
3	Control plant pests and reduce dominance	Control willow (grey and crack varieties), broom, lupins, false tamarisk Didymo surveillance and prevention
4	Control animal pests and reduce dominance	Control cats, mustelids, hares, rabbits, possums, thar, etc. Historical monitoring of predators on Lake Clearwater Island
5	Protect/enhance threatened flora and fauna populations	Surveying and monitoring habitat for distribution and abundance
6	Conserve/interpret historical/cultural sites	Inventory and monitoring state of Takiwa
7	Recognise and manage the compatibility of ecosystem restoration with sustainable land-use	Concessions management, economic development/opportunity, and understanding land-use intensification
8	Recreational use/interpretation	Increase information to visitors and monitor visitor impact Develop recreational opportunities that promote the value and care of wetlands
9	Community awareness/participation	Incorporate local knowledge and acknowledge its importance Empower/encourage community involvement Listen to community needs/wants/goals Help communities to take responsibility for their impacts/issues Community support/participation is essential to make a difference

Objective one, 'protect wetland area and prevent further loss,' is the motivation for research into the ignition thresholds of grassland fuels. Fire could destroy significant sensitive areas within the Hakatere Conservation Park. Throughout summer and autumn, the Ashburton Lakes basin regularly experiences very high to extreme fire danger levels (Department of Conservation, 2008c). Figure 1.5 shows the natural distribution of dead exotic grasses interspersed with dead tussocks in

Hakatere Conservation Park. Off-road vehicle tracks are common to the area (Figures 1.6 and 1.7). Fire danger is exacerbated by two key factors: land-use increase by field workers or recreational users, and land-use change. Increased public access to land, alongside more public knowledge of new and existing recreational areas, cause more people to visit sensitive grasslands and wetlands, thereby augmenting fire risk. Land-use change is leaving substantial areas un-grazed, causing grassland fuel loads to increase. These factors increase ignition risk, and the likelihood of high-intensity fires that are difficult to control. Understanding the fire risk from different ignition sources is important in order to meet this first objective.

Figure 1.5 Distribution of tussock and exotic grasses in Hakatere Conservation Park.

Figure 1.6 View of four-wheel drive (4WD) tracks on tussock grasslands.

Figure 1.7 Close-up of exotic grass encroaching onto 4WD tracks.

1.4 Rural Fire Management in New Zealand

The New Zealand Fire Service Commission's (NZFSC) main roles are to educate the public about fire safety, to prevent fires and mitigate against fire risk, and to provide services for fire suppression and extinction. The NZFSC reports to the Minister of Internal Affairs and is responsible for administering the Fire Service Act 1975 and the Forest and Rural Fires Act 1977 (Dudfield, 2000; Department of Internal Affairs *et al.*, 2003). The two Acts are administered by the New Zealand Fire Service (NZFS), and the National Rural Fire Authority (NRFA). The NZFS is primarily responsible for protecting people and property from fire in urban vicinities; however, each year the NZFS attends between 4,000 and 5,000 fires beyond urban boundaries (Dudfield, 2000). The NRFA is responsible for coordinating rural fire management activities, setting standards, providing technical advice, and facilitating monitoring services (National Rural Fire Authority, 2009). There are 86 Rural Fire Authorities, coordinated by the NRFA, which are responsible for fire suppression, prevention, and protection. They include DOC for state areas, the New Zealand Defence Force for defence areas, Rural Fire District Committees for specially Gazetted areas, and Territorial Authorities for all other areas.

DOC is the single largest Rural Fire Authority, responsible for managing over 15 percent of New Zealand's land for fire control, and contributing at least $7.6 million per annum to the cost of fire suppression resources and activities (Department of Internal Affairs *et al.*, 2003; Department of Conservation, 2009a). Fire management activities for public conservation land, unoccupied crown land, and a one kilometre margin surrounding these land-types, are DOC's responsibility. Personnel include approximately 1,000 firefighters, 350 Crew Leaders, 100 Fire Managers, and 21 Fire Control staff. Available equipment consists of at least 134 fire vehicles, 445 pumps, 212,000 m of hose, 185 collapsible water storage dams, 1600 radios, 127 repeaters, and 120 helicopter support units (Department of Internal Affairs *et al.*, 2003). DOC staff and equipment respond to about 150 to 200 fires annually (Dudfield, 2000).

Many rural fire management decisions rely on the New Zealand Fire Danger Rating System (NZFDRS) as a decision support tool. Section 1.5 explains the principal components of the NZFDRS, which are used to predict fire potential and to indicate fire suppression requirements. Fire weather is monitored throughout the country to assist fire managers with decision-making. Ongoing research aims to improve the NZFDRS, and adapt it to New Zealand's unique needs (Fogarty *et al.*, 1998; Dudfield, 2000; Alexander, 2008).

The Christchurch branch of Scion (a Crown Research Institute) is the main organisation responsible for conducting rural fire research in New Zealand (Scion, 2009). Scion's main strategy is to strengthen New Zealand's economy through research and development programmes, and by adhering to four strategic goals: 1) increase profitability of New Zealand's forest industries, 2), optimise the value of marginal land, 3) accelerate growth of the bioeconomy, and 4) maximise the quality and impact of Scion's science. Fire research strengthens the understanding of fire processes, and provides knowledge to help safeguard important resources and the landscape. Anderson and Pearce (2008) explain the main objectives of fire research in New Zealand (Table 1.11). Fire management and research is based on the "4R's" of emergency management: reduction, readiness, response, and recovery. As fire behaviour is a dynamic process, it is important that fire management decisions be based on accurate and thorough scientific knowledge. Fire managers must play an active role in closing the fire knowledge gap, so that New Zealand's landscape can be protected for future generations.

Table 1.11 Key objectives of rural fire research in New Zealand (adopted from Anderson & Pearce, 2008; Anderson, S.A.J., personal communication, October 30, 2009).

Objective	Research	Anticipated Result
1	Reduction of wildfire hazard	Description of the rural fire hazardscape and the human/social processes contributing to wildfire risk
2	Application of the NZFDRS to enhance readiness	Improvement of the NZFDRS as a decision support tool for warning of wildfire hazard and improving readiness
3	Tools to support wildfire response	Tools and guidelines to promote safe and effective decision-making
4	Improved community recovery	An understanding of community resilience to and recovery from wildfires

1.5 The New Zealand Fire Danger Rating System (NZFDRS)

Fire danger conditions are determined on a daily basis using the New Zealand Fire Danger Rating System (NZFDRS). This system was first implemented in New Zealand in 1980 from the Canadian Forest Fire Danger Rating System (CFFDRS) (Valentine, 1978; de Groot, 1987; Stocks *et al.*, 1989; Forestry Canada Fire Danger Group, 1992; Fogarty *et al.*, 1998). Fire danger is "a general term used to express an assessment of both fixed and variable factors of the fire environment[1] that determine the ease of ignition, rate of spread, difficulty of control, and fire impact" (Merrill & Alexander, 1987, p.14). Fire danger rating is achieved by assessing and integrating the factors affecting fire danger, and is expressed in qualitative/numerical indices (Chandler *et al.*, 1983; Stocks *et al.*, 1989). Fire managers can use the NZFDRS to determine when fire danger is greatest, to predict how a fire will behave, and to determine suppression requirements and/or other mitigation

[1] The fire environment is known as "the surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determine fire behaviour" (Merrill & Alexander, 1987, p.14).

measures. Figure 1.8 illustrates the different components of the NZFDRS, and how the NZFDRS contributes to fire management decision-making.

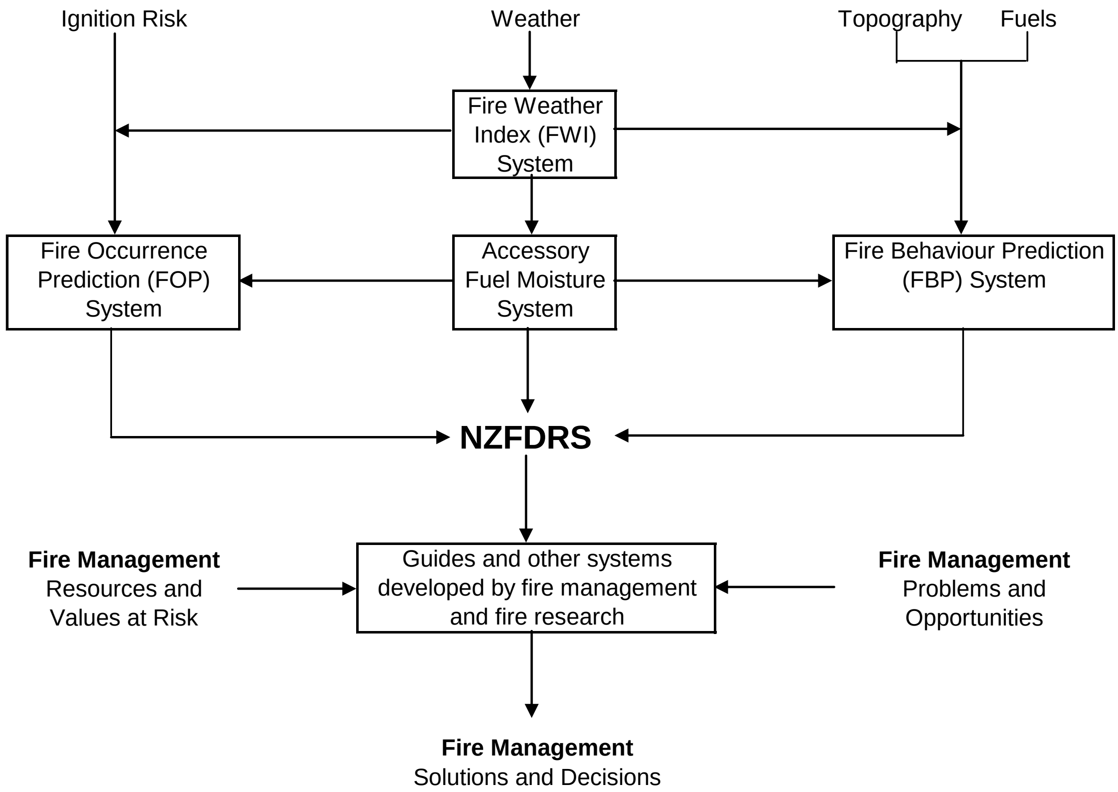

Figure 1.8 Structure of the New Zealand Fire Danger Rating System and its relation to fire management (Fogarty *et al.*, 1998; Anderson, 2005).

The structure of the NZFDRS (Figure 1.8) has not been modified from the original CFFDRS, nor have the four subsystems been completely adapted for use in New Zealand's unique fire environment (Fogarty *et al.*, 1998). Scion's Rural Fire Research Group is focused on adapting the system to New Zealand fuel types so that higher confidence levels can be placed in its use and fire danger predictions (Anderson, 2005). Presently, the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) subsystems are being used. The Accessory Fuel Moisture (AFM) and Fire Occurrence Prediction (FOP) subsystems need to be developed for use in New Zealand before they can be implemented. The following sections (1.5.1 and 1.5.2) explain how the FWI and FBP Systems function. A description of the fire danger class scheme is included in section 1.5.3.

1.5.1 The Fire Weather Index (FWI) System

The FWI System is a core component of the NZFDRS, which has been in use for almost 30 years (Anderson, 2005). It is used to account for how fuel moisture and wind affect ignition potential and fire behaviour (de Groot, 1987; Stocks *et al.*, 1989; Anderson, 2005). The reasons for its selection over other similar systems are five-fold: 1) it is simple and user friendly; 2) it has been developed based on sound science; 3) it has outstanding interpretive backup; 4) the system was developed for pine forests; and 5) the similarity of New Zealand and British Columbia's (Canada) temperate maritime climates (Valentine, 1978). These criteria are still applicable to its present use (Fogarty *et al.*, 1998; Anderson, S.A.J. & Teeling, personal communication, February 4, 2010).

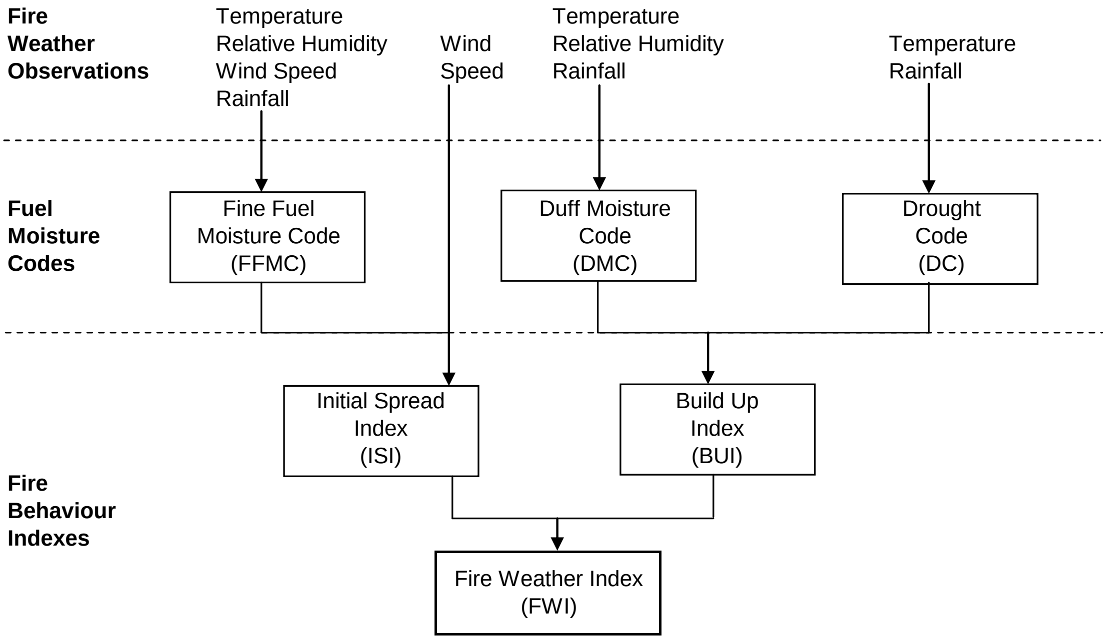

Figure 1.9 Structure of the Fire Weather Index System (Fogarty *et al.*, 1998; Anderson, 2005; 2009).

The six components of the FWI System (Figure 1.9) consist of three fuel moisture codes and three fire behaviour indices. These numerical components are based on weather observations for a reference fuel type: mature jack pine (*Pinus banksiana*) or lodgepole pine (*Pinus contorta*) on flat terrain (Anderson, 2005; 2009). Principal weather inputs are measured at 1200 local standard time (LST) and consist of dry-bulb temperature, relative humidity, wind speed (measured in an open clearing at a height of 10 m), and rainfall accumulation from the last 24 hours. The National Rural Fire Authority, Rural Fire Authorities, and several other organisations, record these observations 365 days a year at over 150 Remote Automatic Weather Stations throughout New Zealand (National Rural Fire Authority, 2009). Although calculated at 1200 LST, the fuel moisture codes and indices are intended to represent peak fire danger conditions at about 1600 LST. The codes and indices can also be calculated hourly (Alexander *et al.*, 1984; Van Wagner, 1987; Lawson & Armitage, 2008)

The three fuel moisture codes depend on the current day's weather, and the value from the previous day's calculation (Stocks *et al.*, 1989). For example, if it has rained, moisture is added to the code-value, and if it is dry, moisture is subtracted. The higher the moisture code value, the lower the fuel moisture content. The Fine Fuel Moisture Code (FFMC) represents the moisture content of fine litter and grasses 1 to 2 cm deep, and indicates ignition potential. The Duff Moisture Code (DMC) represents the moisture content of the duff layer, consisting of loosely compacted organic material 5 to 10 cm deep, and indicates the potential for combustion in this layer. The Drought Code (DC) represents the moisture content of compacted organic material 10 to 20 cm deep, and indicates the potential for deep-seated burning (Van Wagner, 1987). Each moisture code has a time lag and a rainfall threshold (Table 1.12). If rainfall is lower than this threshold value, the code value does not decrease (Anderson, 2009).

Table 1.12 Characteristics of the fuel moisture code components of the FWI System (from Anderson, 2009).

Fuel Moisture Code	Value Range	Rain Threshold (mm)	Time Lag (days)
FFMC	0 to 101	0.6	0.667
DMC	0 to ~150	1.5	15
DC	0 to ~800+	2.8	53

The three fire behaviour indices are broken down into two intermediate, and one final fire behaviour index. They are formed by combinations of the moisture codes and wind speed (Stocks *et al.*, 1989; Anderson, 2005; 2009). The Initial Spread Index (ISI) combines the FFMC with wind speed and indicates fire spread potential without considering fuel quantity. The Buildup Index (BUI) combines the DMC and DC and indicates combustion potential of all available fuel. The FWI combines ISI and BUI to represent the potential intensity of a spreading fire. As the risk of fire intensifies, the values of these three indices increase. Values range from zero to about 200 depending on the index (Table 1.13), and provide fire managers with an indication of suppression requirements and potential fire behaviour. It must be stressed that the FWI value only provides an indication of fire intensity, which is a measure of the heat release per unit length of the fire front, expressed in kW/m. By examining values of the other fire behaviour indices of the FWI System, managers can gain an indication of likely fire size (m^2) and extent (m), as well as burning time (Anderson, 2009).

Table 1.13 Characteristics of the fire behaviour index components of the FWI System (from Anderson, 2009).

Fire Behaviour Index	Value Range
ISI	0 to ~100
BUI	0 to ~200
FWI	0 to ~150

1.5.2 The Fire Behaviour Prediction (FBP) System

The FBP subsystem of the NZFDRS accounts for fire behaviour in fuel types other than the mature pine fuel reference used for the FWI System and considers differences in topography (Stocks *et al.*, 1989; Anderson, 2005; 2009). The primary and secondary outputs of the FBP System are listed in Table 1.14. These outputs are determined by fuel type, slope, and prevailing weather conditions, including wind speed and elements of the FWI System (Forestry Canada Fire Danger Group, 1992; Anderson, 2005; 2009). A simple elliptical fire growth model is used to determine fire size, shape, and area and perimeter growth rates. It assumes that a fire will spread in an elliptical shape, as long as fuel and terrain are uniform, and wind speed is constant. The FBP System allows fire managers to organise appropriate fire suppression actions. Forestry Canada Fire Danger Group (1992) provides a full account of the development of the FBP System.

Table 1.14 Primary and secondary outputs of the Fire Behaviour Prediction System (from Anderson, 2009).

Primary	Secondary
Rate of spread (ROS)	Flank/back fire ROS
Fuel consumption	Fire spread distance
Head fire intensity	Flank & back fire intensity
Fire description	Elliptical fire area & perimeter
	Rate of perimeter growth
	Length:breadth ratio

Both New Zealand and Canada have used an empirical approach to developing the FBP System. A combination of data and records from experimental fires in the field, prescribed fires, and wildfires has been correlated with elements from the FWI System to produce outputs for different fuel types (Stocks *et al.*, 1989; Anderson, 2005; 2009). Figure 1.10 shows how different elements contribute to the entire FPB System. Seven broad fuel types are used for fire behaviour assessment in New Zealand: 1) Pine Plantation, 2) Logging Slash, 3) Indigenous Forest, 4) Pasture Grassland, 5) Crop Stubble, 6) Tussock Grassland, and 7) Scrublands (Anderson, 2009). Fire danger is based on fire intensity, represented by the FWI. The fire danger class scheme indicates the difficulty of fire control under different conditions (Alexander, 2008).

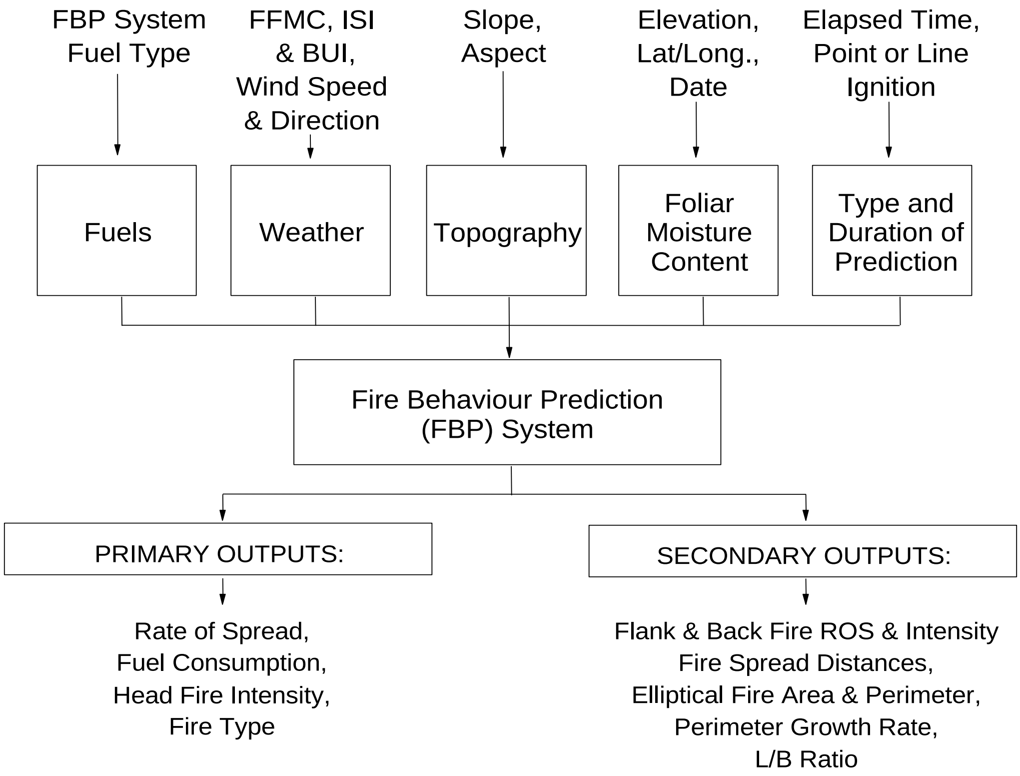

Figure 1.10 Structure of the Fire Behaviour Prediction System (FBP) (after Forestry Canada Fire Danger Group, 1992).

1.5.3 Fire Danger Class Scheme

Alexander (2008) developed the fire danger class scheme for New Zealand based on the FBP System and Byram's (1959) concept of fire intensity. Byram (1959) considered a single spreading fire in a standard fuel of mature pine and represented its fire intensity by:

Equation 1.1 $$I = H \times w \times r$$

where I = fire intensity (kW/m), H = fuel heat of combustion (generally assumed to be ~18,000 kJ/kg, but can be other values), w = fuel consumed in active flaming front (kg/m^2), and r = rate of fire spread (m/s) (Alexander, 1982). This equation can be related to the three fire behaviour indices of the FWI System, where 'I' represents FWI, 'H' is a constant value, 'w' represents BUI, and 'r' represents ISI. Fire intensity is related to flame size, and can be used to indicate suppression difficulty for various fuel types (Byram, 1959; Alexander, 2000; Anderson, 2009). Alexander (2008) devised the danger class criteria for Forests, Grasslands, and Scrublands. The five danger classes are LOW, MODERATE, HIGH, VERY HIGH, and EXTREME. Table 1.15 explains each class in terms of fire potential and fire suppression needs. The fire danger class criteria are based on fuel types from the FBP System.

Table 1.15 Fire danger class scheme and descriptions (adopted from Alexander, 2008).

Fire Danger Class	**Description of Probable Fire Potential and Implications for Fire Suppression †**	**Nominal Max. Flame Height**
LOW	New fire starts are unlikely to sustain themselves due to moist surface conditions. However, ignitions may take place near large and prolonged or intense heat sources (e.g., camp fires, windrowed slash piles) but the resulting fires generally do not spread much beyond their point of origin and, if they do, control is easily achieved. Mop-up or complete extinguishment of fires that are already burning may still be required provided there is sufficient dry fuel to support smouldering combustion*. Colour code is GREEN.	no visible flame
MODERATE	From the standpoint of moisture content, fuels are considered to be sufficiently receptive to sustain ignition and combustion from both flaming and most non-flaming (e.g., glowing) firebrands. Creeping or gentle surface fire activity is commonplace. Control of such fires is comparatively easy but can become troublesome as fire damages can still result and fires can become costly to suppress if they aren't attended to immediately. Direct attack around the entire fire perimeter by firefighters with only hand tools and back-pack pumps is possible. Colour code is BLUE.	up to 1.3 metres
HIGH	Running or vigorous surface fires are most likely to occur. Any fire outbreak constitutes a serious problem. Control becomes gradually more difficult if it's not completed during the early stages of fire growth following ignition. Water under pressure (from ground tankers or fire pumps with hose lays) and bulldozers are required for effective action at the fire's head. Colour code is YELLOW.	1.4 to 2.5 metres
VERY HIGH	Burning conditions have become critical as the likelihood of intense surface fires is a distinct possibility; torching and intermittent crowning in forests can take place. Direct attack on the head of a fire by ground forces is feasible for only the first few minutes after ignition has occurred. Otherwise, any attempt to attack the fire's head should be limited to helicopters with buckets or fixed-wing aircraft, preferable dropping long-term chemical fire retardants. Until the fire weather severity abates, resulting in a subsidence of the fire run, the uncertainty of successful control exists. Colour code is ORANGE.	2.6 to 3.5 metres
EXTREME	The situation should be considered "explosive" or super critical. The characteristics associated with the violent physical behaviour of conflagrations or firestorms is a certainty (e.g., rapid spread rates, crowing in forests, medium- to long-range mass spotting, firewhirls, towering convection columns, great walls of flame). As a result, fires pose an especially grave threat to persons and their property. Breaching of roads and firebreaks occurs with regularity as fires sweep across the landscape. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution. The only effective and safe control action that can be taken until the fire run expires is at the back and along the flanks. Colour code is RED.	3.6+ metres

† THE ABOVE SHOULD NOT BE USED AS A GUIDE TO FIREFIGHTER SAFETY, AS FIRES CAN BE POTENTIALLY DANGEROUS OR LIFE-THREATENING AT ANY LEVEL OF FIRE DANGER!

* General rule(s) of thumb: certainly when Drought Code (DC) exceeds about 300 and/or Buildup Index (BUI) is greater than around 40, one can generally expect ground or subsurface fires. Please note however, these benchmark values are for moderately well-drained sites, but in actual fact they will vary according to soil and drainage conditions and should bedetermined locally on the basis of past wildfire suppression and/or prescribed burning experience.

Grassland fire danger classification uses the O-1b (Natural/Standing Grass) fuel type model from the FPB System (Forestry Canada Fire Danger Group, 1992; Fogarty *et al.*, 1998; Alexander, 2008; Anderson, 2009). The danger class depends on ISI and degree of curing (Figure 1.11), where degree of curing "represents the proportion of cured and/or dead material in a grassland fuel complex expressed as a percentage (%) of the total" (Alexander, 2008, p. 10). Curing is defined as the death or drying out of grass as a natural process in its life cycle (annuals), or as a reaction to drought (perennials) (Cheney & Sullivan, 2008). The degree of curing value is supplied by the user and can be assessed by a visual estimate (Garvey & Millie, 1999; Alexander, 2008), or by levy rod assessment in the field (Anderson *et al.*, 2005; Bushfire CRC, 2006), or by satellite assessment (Dilley *et al.*, 2004; Arroyo *et al.*, 2008). Research is investigating other ways of assessing degree of curing using improved remote sensing technology and pasture growth models (Daily *et al.*, 2009; Martin *et al.*, 2009).

The percent of cured vegetation is a critical factor to consider when predicting probability of ignition or fire behaviour. If curing is less than 50 percent, fires will not generally spread. However, once between 75 and 90 percent cured, fires will begin to spread easily, and above 95 percent, fire spread can become very fast in high wind (Cheney *et al.*, 1998; Cheney & Sullivan, 2008). Grass is most flammable when it is 100 percent cured and has low moisture content; hence, an understanding of the relationship between fire danger levels and degree of curing is crucial, especially when grasslands are above 90 percent cured at the end of summer and throughout autumn. When grasslands are not cured the probability of ignition is low, but when curing begins the ignition probability increases, and fires can slowly begin to spread.

1.5.4 Summary of the NZFDRS

The NZFDRS relies on two major subsystems: the FWI and FBP Systems. From these systems, a fire danger class scheme has been developed based on different inputs depending on fuel type. Currently, fire danger class criteria are available for three fuel types: Forest, Grassland, and Scrubland. The other two subsystems of the NZFDRS, the Fire Occurrence Prediction System and the Accessory Fuel Moisture System, have not been developed for use in New Zealand, and development has been slow in Canada. The primary function of the NZFDRS is to determine fire potential and support fire management decision-making. Ongoing research aims to develop models that predict the probability of ignition in different fuel types along with appropriate weather and topography inputs.

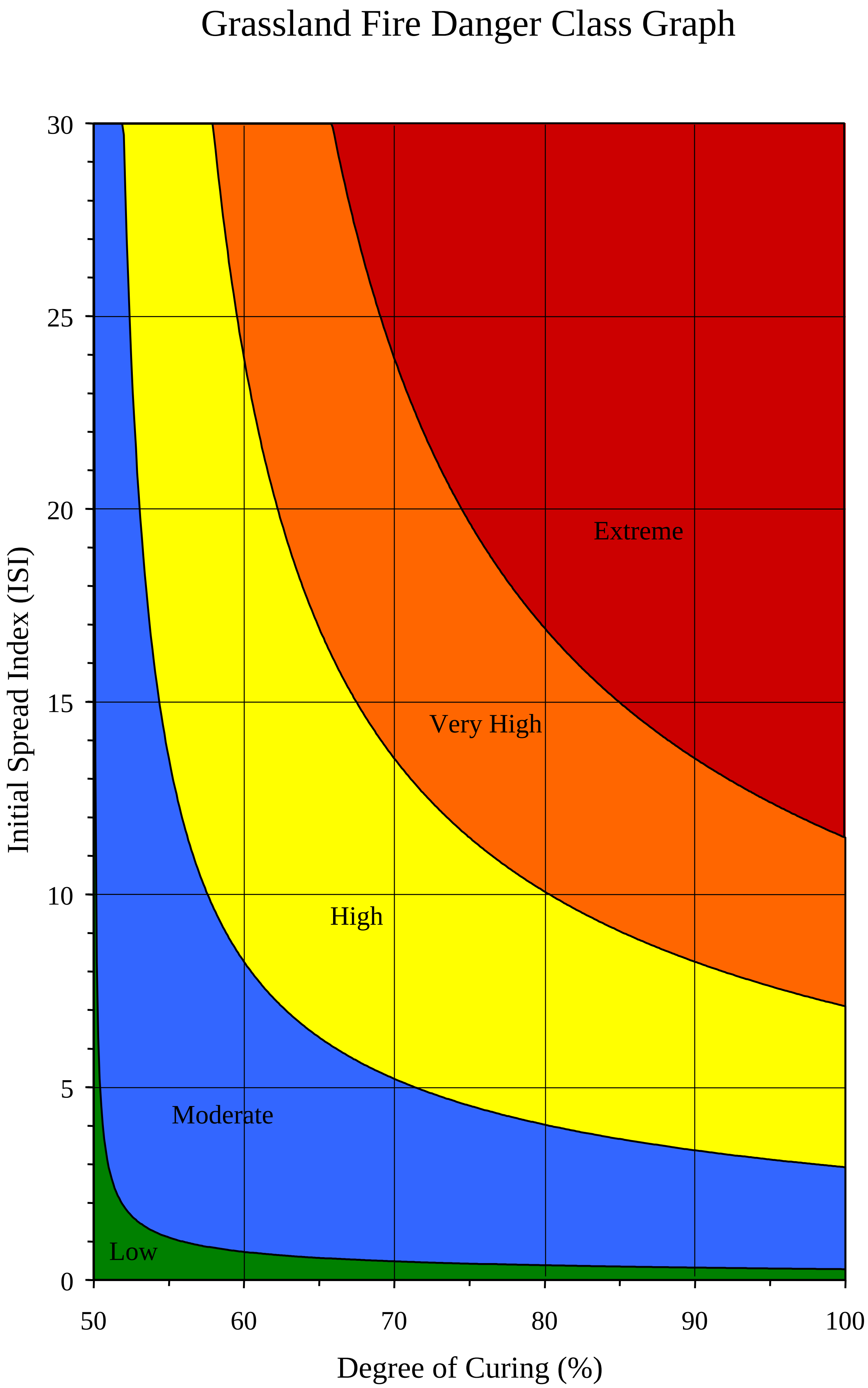

Figure 1.11 The Grassland Fire Danger Class Graph (from Alexander, 2008).

1.6 Study Overview

1.6.1 Study Structure and Significance

The main incentives for conducting this study include, but are not limited to, the protection of the Ō Tū Wharekai Wetland and Hakatere Conservation Park, other Canterbury grasslands, and ultimately, of other important wilderness areas in New Zealand. In order to prevent further loss of wetlands and other sensitive areas, DOC needs accurate information about the ignition thresholds of grassland fuels. DOC needs to monitor grassland areas carefully, and results from laboratory and field experiments will help managers predict the probability of grassland ignitions from different ignition sources. Some ignition sources of concern are off-road vehicles (for example, four-wheel drive (4WD) trucks/utility vehicles, motorbikes, and all-terrain vehicles (ATVs)), outdoor power equipment, machinery, campfires, gas cookers, and malicious intent. This project investigated the ignition of wildfires by simulating five different ignition sources: hot metal, hot carbon, metal sparks, organic embers, and open flame. Ignition thresholds of fully cured/dead tussock and exotic grass fuels were explored for different moisture content levels. Wind speed was varied, but ambient temperature and relative humidity were kept relatively constant. The ignition thresholds were reported for different scenarios involving ignition source, moisture content level, wind speed, and other variables.

Results of this study will be used by DOC to create decision-support tools for fire managers throughout New Zealand, but especially for the Canterbury region. To reduce fire risk, DOC could implement activity controls such as restricting vehicle and machinery access, closing high-risk areas to the public, and/or increasing the number of rural fire teams on stand-by. Fire management decisions need to be guided and supported by science-based knowledge and tools. This research aims to aid DOC staff with applying these types of activity controls. The research could also be used for fire investigation purposes.

1.6.2 Research Objective and Questions

The prevailing objective of this research was to determine threshold conditions for fire ignition in grasslands. Moreover, the aim was to provide a scientific basis for DOC to mitigate against wildfires through decision-support tools for activity controls in Canterbury. The prevailing research question was, “what are the ignition thresholds in grasslands from different ignition sources?” The question was broken down into five sub-questions to provide a better focus for the project:

1) At what moisture content levels will grass fuels ignite from different ignition sources?

2) What is the time-to-ignition using the different ignition sources?

3) At what contact temperatures will grass fuels ignite?

4) At what carbon (vehicle exhaust emission) temperatures will grass fuels ignite?

5) Under what conditions will grass fuels ignite from sparks (metal and organic)?

1.6.3 Thesis Structure

- Chapter two contains a literature review of key terms and concepts, significant ignition sources of concern and their ignition thresholds, and important grass fires that have occurred in Canterbury over the last seven years.
- Chapter three provides the methodology for laboratory and field experiments.
- Chapter four describes the experimental results and analysis.
- Chapter five is a discussion of the results, and includes guidelines for management applications and decision-support tools.
- Chapter six contains the conclusions, with management implications for activities associated with high fire risk and key research recommendations.
- Chapter six is the conclusion, with management implications for activities associated with high fire risk and key research recommendations.

Chapter 2. Fire Ignitions in Grassland Fuels: A Literature Review

2.1 Introduction

This chapter presents a detailed review of research regarding the fire process, ignition thresholds, and important ignition sources. A discussion on variables that affect ignition thresholds, and a summary of approaches to investigating and modelling ignition probability is included. Methodology into the ignitibility of grasses and other fine fuels can be quite inconsistent between researchers, comprising different laboratory and field conditions, many variables, and a range of ignition sources. Mechanisms of the five ignition sources investigated in this study, and of other important ignition sources, are examined. This incorporates research on ignition thresholds of shrub, grass, and other fuels, as there is insufficient literature that concentrates solely on grassland fuels. At the end of the chapter there is a brief account of several significant Canterbury grass fires, which were caused by some of the reviewed ignition sources. Fire records and reports can provide useful insight into ignition causes and thresholds, and can be used to help prevent future fires from occurring, or to expand on previous research.

2.2 Key Terms and Concepts

2.2.1 The Fire Process

Fire is an extremely complex process governed by chemical and physical principles. Under laboratory conditions, fire exhibits considerable variability, which is augmented by environmental conditions in the open. This variability makes the fire process difficult to fully understand. Essentially, fire is the result of a number of chemical reactions which produce heat and light energy; it is the reverse process of photosynthesis, much quicker, and more complicated (Ford, 1995; Pyne *et al.*, 1996; DeHaan, 2002; Lentini, 2006; Cheney & Sullivan, 2008). Fire fundamentals can be explained by the fire triangle, where oxygen, heat, and fuel must be present for fire to exist. The burning/oxidising phenomenon begins with endothermic and exothermic reactions that absorb and release energy in the preignition phase. Exothermic reactions release energy in the combustion phase. Ignition represents the transition between preignition and combustion. The remainder of this chapter considers fire processes specific to vegetation fuels.

Preignition can occur with or without oxygen, and is the phase where fuel is heated to the ignition temperature. Initially, the fuel's cellular structure begins to dehydrate, eliminating free and bound water. This is followed by volatilisation of other compounds. In grass fuels, slow heating below 250ºC results in dehydration and charring (exothermic reaction). Char usually burns slowly by glowing combustion, otherwise known as smouldering. Fast heating usually occurs above 250ºC when water is not present, and results in the volatilisation of cellulose (Cheney & Sullivan, 2008). This is known as pyrolysis (endothermic reaction), the chemical breakdown of fuel in which long-chain molecules are broken down into smaller-chain molecules (Pyne *et al.*, 1996; DeHaan, 2002; Babrauskas, 2003). This produces tar and highly unstable gases which react strongly with one another and release considerable heat in flaming combustion.

Ignition usually occurs when the fuel reaches the temperature that allows it to transition from preignition to glowing or flaming combustion (Pyne *et al.*, 1996). It is accompanied by the presence of a flame or glow (Chandler *et al.*, 1983). Once the fuel has ignited, energy release allows adjacent fuel to ignite; therefore, the external heat or ignition source is no longer required, characterising combustion as self-sustaining.

After ignition, the fire process usually exhibits a combination of glowing and flaming combustion. Combustion is defined as a self-sustaining oxidation reaction occurring at high temperatures (Babrauskas, 2003). After flaming combustion has burned all of the gases produced by pyrolysis, the remaining carbon continues to burn by glowing combustion. Simple forms of overall combustion and glowing combustion are represented by the following reactions:

Overall Combustion: $C_6H_{10}O_5 \text{ (cellulose)} + 6O_2 \rightarrow 6CO_2 + 5H_2O + \text{heat}$

Glowing Combustion: $C + O_2 \rightarrow CO_2 + \text{heat}$

When combustion is complete, cellulose has been converted into energy, and other compounds, elements and minerals are left behind as ash. Smoke is produced by incomplete combustion and water vapour.

Flammability can be considered to include three separate terms: ignitibility, sustainability, and combustibility (Anderson, 1970; Mak, 1988). Ignitibility can be defined as the time it takes for fuel to ignite. This comprises the preignition and ignition phases of the burning process. Sustainability is the ability for the fuel to continue burning, and can be associated with fire rate of spread. Combustibility is the rate at which the fuel burns, and can be related to fire intensity. A definition of flammability, comprising all three terms, is the capability for fuel to ignite and sustain a fire at a given intensity. Fuel flammability is highly affected by intrinsic fuel properties.

Fuel properties are very important to the fire process, as they affect the way a fire burns (Chandler *et al.*, 1983; Pyne *et al.*, 1996; Tolhurst & Cheney, 1999; Cheney & Sullivan, 2008). Intrinsic properties refer to internal fuel characteristics that cannot be changed, such as fuel chemistry, density, and heat of combustion. Extrinsic properties affect fire behaviour, and include fuel loading, fuel size and shape, compactness, and arrangement. Fuel loading (usually reported in t/ha) represents the weight of fuel per unit area, based on oven-dry weight. As fuel loading increases, fires burn more severely, and are often larger and harder to control. Grass fuels have small particles and high surface area-to-volume ratios. They dry quickly because they are highly exposed to the surrounding environment. This causes them to burn more readily than fuels with larger particles and lower surface area-to-volume ratios such as logs. Compactness influences fire spread rates and changes in moisture content (MC), because it affects oxygen and heat levels that can flow through the fuel. Highly compact fuels react slowly to humidity changes, and have less oxygen available for fire ignition. Grass fuel arrangement is generally vertical, compared with litter and thatched layers, and windblown trees which are horizontally arranged. Fuel condition, such as the percentage cured, also affects fire behaviour. As previously mentioned (Chapter One), grass that is less than 50% cured usually cannot sustain fire (Cheney & Sullivan, 2008). Fuel properties also affect ignition thresholds. Fuel MC is closely related to ignition thresholds and is explained in detail in the following section. Fuel variability also contributes to the range of thresholds reported for different fuels and species.

2.2.2 Ignition Thresholds and Associated Concepts

Ignition thresholds refer to conditions which cause ignition behaviour to change (Plucinski & Anderson, 2008). These conditions cause fuel to successfully transition from non-flaming to flaming ignition. This study reports ignition thresholds in terms of ignition source temperature and/or dead fuel MC, and any other prevailing conditions, at which there is more than a 50% probability of ignition success. Probability of ignition success, or ignitibility, refers to the likelihood of flaming ignition occurring for a given set of conditions (Babrauskas, 2003). Other studies and reports consider similar definitions. For example, the ignition threshold for some forest fuels exists at around 320ºC (Ford, 1995; Pyne *et al.*, 1996). Below this contact temperature, flaming ignition does not occur. Woodman and Rawson (1982) reported ignition thresholds of radiata pine (*Pinus radiata*) litter from open flame at MC < 20%, above this MC ignition did not occur. Anderson and Anderson (2010) reported that marginal ignition from an ordinary lighter was between 30 and 36% MC of elevated dead gorse (*Ulex europaeus*), with no probability of ignition above 36% MC of elevated dead gorse.

Fuel MC is a highly significant variable affecting the ignition thresholds of fuels. In many studies it is the single most important variable (e.g., Wilson, 1985; de Groot *et al.*, 2005; Plucinski & Anderson, 2008; Anderson & Anderson, 2010; Dimitrakopoulos *et al.*, 2010). MC is the amount of moisture present in the fuel, expressed as a percentage of the fuel's oven-dry weight. It can exceed 100% because fuel can hold more water weight than its own weight in cells, between cells, and on its surface (Pyne *et al.*, 1996). Generally, as fuel MC increases, the probability of ignition decreases. In many cases, if a heat source is applied to fuel for an extended period of time, most of the fuel moisture will evaporate. Regardless of the ignition source, it is generally agreed that as MC of the fuel source rises, the time-to-ignition increases (Gill *et al.*, 1978; Dimitrakopoulos & Papaioannou, 2001; Dimitrakopoulos *et al.*, 2006).

Dead grass fuel MC is a significant variable affecting ignitibility, especially if the fuel 100% cured (Pyne *et al.*, 1996; Cheney & Sullivan, 2008). Tussock grasslands usually have a build-up of dead material underneath live grasses (Winterbourn *et al.*, 2008). This can result in spreading fires if the vegetation is more than 50% cured, and conditions are favourable for ignition (Cheney & Sullivan, 2008). Dead grass fuel MC is highly influenced by weather due to its small particles and low surface area to volume ratios (Pyne *et al.*, 1996). This causes the fuel to absorb moisture quickly during rain. High relative humidity also increases fuel MC. After rain, if relative humidity is low and ambient temperature is high, moisture rapidly evaporates. Grass fuels continually absorb or evaporate moisture from the environment until they reach equilibrium. The ability for dead grass fuels to quickly respond to environmental changes exacerbates fire risk in dry conditions.

Live grass fuel MC generally slows or inhibits fire spread (Pyne *et al.*, 1996; Cheney & Sullivan, 2008). It is primarily influenced by physiological changes stimulated by seasonal change (Pyne *et al.*, 1996). No literature was found that attempted to model the ignitability of solely live grass fuels. However, Weise (2005) successfully modelled ignition and fire spread of four chaparral species, and found that wind speed, slope, MC, species, and ambient temperature affected ignition success, with the model correctly classifying 94% of observations. Chandler *et al.* (1983) stated that if live fuel MC drops below 75%, fires will burn rigorously in forest fuels. A study investigated the ignitibility of leaves from live California chaparral species and live tree species from Utah, by exposing them to hot gases, and reported that ignition temperatures varied from 227 to 453ºC depending on species (Fletcher *et al.*, 2007). In addition, as leaf thickness and MC increased, ignition temperature decreased, and time-to-ignition increased. Gill and Moore (1996) exposed leaves of 50 live Australian species to piloted ignition in a muffle furnace at 400ºC, and also found that increased leaf thickness and MC cause time-to-ignition to increase. Another study found a positive relationship between live conifer MC, and time-to-ignition (Xanthopoulos & Wakimoto, 1993).

Extinction occurs when combustion can no longer be sustained due to lack of heat, oxygen, or fuel (Pyne *et al.*, 1996). Some studies consider moisture of extinction, which is the fuel MC at which a fire can no longer be sustained and will self-extinguish. Luke and McArthur (1986) report that eucalypts (*Eucalyptus* spp.) self-extinguish at 16 to 20% dead MC, whereas some conifers can sustain fire up to 30% MC. Moisture of extinction cannot be compared with ignition thresholds because conditions can differ, and moisture of extinction is related to changes in environmental conditions, such as relative humidity or rainfall, which cause fires to self-extinguish.

Dead grasses have a moisture of extinction of around 15 to 20% (Babrauskas, 2003; Cheney & Sullivan, 2008). Under light winds (< 2.75 m/s), ignition can occur at 20% dead grass MC, but fire usually does not spread (Marsden-Smedley *et al.*, 2001; Cheney & Sullivan, 2008). Research in Tasmania suggested that the moisture of extinction for buttongrass moorlands (from 3.4 to 30.0 t/ha fuel loading) was at 70% dead fuel MC, when wind speed increased above 1.4 m/s at 1.7 m height (Marsden-Smedley & Catchpole, 1995; Marsden-Smedley *et al.*, 2001). In Tasmanian native grasslands (from 0.2 to 11.9 t/ha fuel loading), Leonard (2009) predicted that fires are sustainable at dead fuel MC of < 24%, suggesting that the moisture of extinction is ≥ 24%. The moisture of extinction for the grass species slender oat (*Avena barbata* Pott. ex Link) was predicted to be about 56% dead MC (Dimitrakopoulos *et al.*, 2010). It is difficult to compare these studies as experimental variables differed; although, they all used drip torches as an ignition source.

The ignitibility of grass fuels is generally much higher than other vegetation types such as needles and leaves (Hogenbirk & Sarrazin-Delay, 1995). This implies that, given the same ignition source and environmental parameters, grass fuels will ignite in a shorter time than other plants. This conclusion stemmed from an analysis that involved ranking the ignitibility of vegetation based on chemical and physical characteristics which was consistent for live and dead fuels (Hogenbirk & Sarrazin-Delay, 1995). This observation has also been reported by other researchers (Pyne *et al.*, 1996; Babrauskas, 2003; Cheney & Sullivan, 2008).

Other parameters affecting ignition thresholds of fuel include wind speed, ambient temperature, and RH. Studies involving open flame or ember ignition sources generally reported that wind presence decreased the probability of ignition (e.g., Sale & Hoffheins, 1928; Pérez-Gorostiaga *et al.*, 2002). However, studies involving contact between fuel and hot objects generally reported that light winds can cause ignitions at lower contact temperatures (e.g., Di Blasi *et al.*, 1999; Pitts, 2007). Cheney and Sullivan (2008) suggested that the probability of ignition in the presence of different wind speeds is directly related to ignition source type. In the field, ambient temperature and RH influence dead fuel MC, but when they change the fuel takes time to respond. They primarily affect dead fuel MC, which is has a significant effect on ignition thresholds (Chandler *et al.*, 1983; Pyne *et al.*, 1996; Cheney & Sullivan, 2008).

Babrauskas (2003, p. 835) notes that although "ignition temperatures of vegetation have been measured by numerous researchers… the reported values are widely discordant" and provides several reasons for these differences. First, similar vegetation types should have similar ignition thresholds, varying only slightly due to differences in chemical composition. However, major differences have been reported which can be attributed to differences in research approaches, equipment, and sample size (Babrauskas, 2003). Second, even at high initial MC values, prolonged exposure of the fuel to a heat source will dry the fuel sufficiently to support ignition. However, some ignition sources cannot sustain heat for a long time, and in these instances the initial fuel MC is important. Furthermore, many studies have not been replicated and there are no universal standards for testing the ignition thresholds of grassland fuels from different ignition sources (Babrauskas, 2003).

Comparisons of ignition thresholds are further complicated by the variety of analyses used in research to date. Many studies have reported the conditions under which the fuel ignites, but have not modelled the probability of ignition (e.g., Bunting & Wright, 1974; Stockstad, 1976; Knight & Hutchings, 1987; Di Blasi *et al.*, 1999; Baxter, 2004; Gonzales, 2008). Logistic regression is commonly used as a reliable way to model probability of ignition (e.g., de Groot *et al.*, 2005; Dimitrakopoulos *et al.*, 2006; Plucinski & Anderson, 2008; Leonard, 2009; Anderson & Anderson, 2010; Dimitrakopoulos *et al.*, 2010). Experimental outcomes are classified as success or failure, depending on whether the fuel ignites or not. A sigmoidal curve is fitted to these outcomes, depending on significant explanatory variables. The model can be solved for a given probability level (usually 0.5) which explains the ignition thresholds.

2.3 Main Ignition Sources of Concern in this Study

The five ignition sources investigated in this study were hot metal, hot carbon, organic embers, metal sparks, and open flame.

2.3.1 Hot Metal (hot vehicle or machinery parts)

Hot metal ignition sources consist of any type of hot metal surface, such as hot exhaust systems or parts on vehicles or machinery. Off-road vehicles and outdoor power equipment commonly contain very hot exhaust systems and/or catalytic converters that can potentially ignite outdoor fuels. Babrauskas (2003) states that ignition by hot surfaces is highly dependent on ignition source size. Many studies do not specify size, or use non-uniformly shaped hot metal ignition sources. Furthermore, references can be difficult to obtain for older studies as they have not been stored electronically (Babrauskas, 2003). This section reviews temperatures of vehicle exhaust systems and hot outdoor power equipment, and summarises studies that investigated ignition temperatures of grass and other fine wildland fuels.

A study of Californian fire-causes from records between 1962 and 1971 revealed that 28% of fires were caused by hot equipment ignition sources (Bernardi, 1974). Among these ignition sources were personal and commercial vehicles, tractors, harvesters, power equipment, and locomotives. Roadside fires caused by hot exhaust systems of automobiles and trucks were the most common, followed by fires caused by power equipment. The study considered ignition sources which caused forest fires, implying that grasslands are subject to higher risk of ignition from these sources, as they contain more flammable fuel types (Bernardi, 1974).

Vehicle exhaust systems take exhaust gas from the engine and expel it out of the tailpipe. They can comprise turbochargers, catalytic converters, spark arresters, and several mufflers which are positioned between the manifold and the tailpipe, usually in that order (Heisler, 1999). Catalytic converters are designed to lower the level of harmful emissions entering the atmosphere from vehicle exhaust systems by converting carbon monoxide, hydrocarbon, and nitrogen oxides to carbon dioxide, steam, and nitrogen. This reaction can only take place at temperatures above 300ºC. Maximum internal temperatures of catalytic converters can reach 900ºC, but outside temperatures are closer to 260ºC. An exhaust system's hottest point is near the manifold, which usually exhibits temperatures between 500 and 550ºC, but can be higher if a turbocharger is present (Heisler, 1999; Cole, 2001; DeHaan, 2002). This temperature can increase by 40ºC after the engine is turned off or during idle, posing significant ignition risk if vehicles are parking on grassy road-side areas (Cole, 2001; Babrauskas, 2003). Exhaust system temperatures generally decrease as exhaust gases pass from the manifold to the tailpipe.

In New Zealand and Australia there are no regulations or standards that limit temperatures of exhaust systems. Yet, some manufacturers conduct their own tests to confirm that exhaust systems, brakes, and electrical vehicle parts do not exceed a certain temperature. These tests usually check temperatures of hot components that could damage the vehicle, or that are within 30 cm of the ground (Knight & Hutchings, 1987; Babrauskas, 2003).

Tests from Californian vehicles (1974 and 1975 models) suggested that catalytic converters increase exhaust system temperatures by about 60ºC (Table 2.1) (Harrison, 1977). This might be true for older vehicles, but advances in technology have changed the efficiency of modern vehicles. Heat shields are usually added to catalytic converters, thereby reducing surface temperature. However, if material becomes trapped between the catalytic converter and the heat shield, it may ignite and fall from the vehicle, potentially igniting ground fuels (Knight & Hutchings, 1987). Further temperature tests are needed to verify this result for modern vehicles.

Table 2.1 Experiments involving temperature measurements of vehicle exhaust systems.

Vehicle Types	Location of Thermocouple	Maximum Measured Temperature, or Temperature Range (ºC)		Reference
1974-1975 California cars (37 various makes including AMC, Plymouth, Chrysler, Ford, Chevrolet, Buick, and VW, 26 with a catalytic converter, 11 without)	Hottest temperatures are usually the catalytic converter. Vehicles without converters usually exhibit hottest temperatures at the first bend of the exhaust system.	Catalytic Converter Equipped	Without Catalytic Converter	Harrison 1977
	Location not specified	531	475	
Motorcycles (50, 100, and 125 cc)	End of exhaust pipe (reported temperatures are maximum temperatures for various speeds 20-60 km/h)	50cc: 170-250 100cc: 90-120 125cc: 110-130		Lai *et al*. 2002
Diesel Trucks (5 with DPF: Dodge 550 HD, Sterling 550 Bullet, International 7400, Ford F-550, GMC Model C5500, and 1 without DPF: Ford F-550)	Temperatures measured on trucks with or without a diesel particulate filter (DPF)	DPF Equipped	Non-DPF Equipped	Gonzales 2008
	Exhaust gas inside tailpipe	403	213	
	Exhaust gas outside tailpipe	368	202	
	Exhaust gas before exhaust cooler	587	~	
	Diesel particulate filter	257	~	
	After diesel particulate filter	375	~	
	Before diesel oxidizing catalyst	292	213	
	Diesel oxidizing catalyst	258	129	
ATVs (4 various makes which were not specified)	Manifold	339 - 585		Baxter 2004
	Halfway along exhaust pipe	232 - 469		
	Before muffler	240 - 469		
	End of muffler	64 - 468		
ATVs (2 Honda Fourtrax ES (350 cc))	Temperatures measured on ATVs with or without an exhaust insulator (EI)	EI Equipped	Non-EI Equipped	Palmu & Baxter 2008
	Immediately after the manifold	~ 105	503	
	Halfway along exhaust pipe	~ 140	~ 385	
	Immediately before the muffler	213	~ 375	
	Muffler	~ 140	~ 305	
	On the end of the exhaust pipe	~ 110	~ 160	

Exhaust pipes of small motorcycles can reach 250ºC when driving up to 60 km/h (Lai *et al.*, 2002). Because this study was concerned with the risk of burns to human skin, only tailpipe temperatures were measured (Table 2.1). If temperature measurements were taken at the manifold they would have been higher because the manifold is usually the hottest part of an exhaust system (Heisler, 1999). Larger off-road motorcycle exhaust systems can reach temperatures high enough to ignite dry, cured grass, especially if the motor has been operating under strenuous conditions such as rough and steep terrain (Taylor, 2007).

In the United States, diesel trucks from 2007 and newer must have a diesel particulate filter (DPF) installed in the exhaust system to reduce large particulate matter (soot) type emissions. The DPF requires an internal temperature of 500ºC in order to work. Gonzales (2008) measured temperatures of the diesel oxidizing catalyst (catalytic converter), and the DPF on five trucks driving at highway speeds (Table 2.1). One truck was used as a control. The average maximum temperature was 375ºC immediately after the DPF. The truck without a DPF recorded 213ºC immediately before the diesel oxidizing catalyst. Ambient temperatures were measured under the DPF at various heights from the ground. The maximum temperature was 282ºC at 42 cm. These measurements indicate that the risk of ignition is higher on trucks equipped with DPFs.

Baxter (2002) determined that all terrain vehicles (ATVs) are a significant fire cause. Temperatures of four different ATV exhaust systems were measured during 16 days of trail riding through various conditions (Baxter, 2004) (Table 2.1). Temperatures reached 585ºC at the manifold and 468ºC at all other points of the exhaust system, and were frequently above 300ºC.

Palmu and Baxter (2008) examined the effectiveness of an insulation system that reduces ATV exhaust system temperatures. Two ATVs were driven for 21.1 km and temperatures were recorded at five points along the exhaust system (Table 2.1). Maximum temperatures were 503ºC at the manifold and 213ºC before the muffler for the regular ATV and insulator-equipped ATV respectively. The insulation system was therefore very successful at lowering ATV exhaust system temperatures.

Hot exhaust manifolds were tested by Fairbank and Bainer (as cited by Babrauskas, 2003) and temperatures of 663ºC were required to ignite dry grass. This is the highest reported temperature compared with all reviewed literature. Harrison (as cited by Babrauskas, 2003) used a rod-shaped electric heating element and found that dry grass ignited at 400ºC when wind speed was 0.9 m/s, for tests lasing 4 minutes; however, according to Babrauskas (2003) exposure time may have been too short. Kaminski (1974) reported that with a pilot flame, flaming ignition of cheat grass (*Bromus tectorum*) occurred at 270ºC. Rallis and Mangaya (2002) reported that glowing ignition of 'fine, dry veld grass' occurred between 250 and 350ºC. Flaming ignition was possible at 400ºC after blowing on the sample.

Kaminski (1974) investigated ignition potential from hot chainsaw mufflers (Table 2.2). Four fuel types were tested including cheat grass. In an environmental chamber set to 35.6ºC, cheat grass containing 6% MC glowed at 330ºC and browned at 270ºC within ten minutes. Flaming ignition was only observed for decayed (punky) wood at 260ºC or higher. Kaminski (1974) suggested that ignition in forest fuels will not occur if chainsaw mufflers remain below 260ºC. Furthermore, lawnmower mufflers can reach 350ºC, representing a significant ignition risk, especially if sparks are produced if the blade strikes gravel or rocks (Babrauskas, 2003).

Pitts (2007) used a hot copper plate to investigate ignition temperatures of common fuels including tall fescue grass (*Festuca arundinacea*), collected in May and in August, cheat grass, and fine Florida grass (a mix of unidentified mowed grasses) (Table 2.2). Samples were conditioned to 10 to 14% MC; but grass was cut into small lengths which did not represent fuels in their natural state. In most cases glowing ignition was observed, which developed into flaming ignition in the presence of wind. Without wind, the lowest temperatures for ignition were between 320 and 380ºC, and with wind ($\leq$ 2.5 m/s) the lowest temperature was 310ºC for all grass fuels but cheat grass (350ºC). Babrauskas (2003) reports that forest fuels can ignite at 350 to 400ºC if exposure time is long enough, which concurs with Pitts' (2007) findings.

Knight and Hutchings (1987) conducted several tests involving dry grass and hot exhaust systems (Table 2.2). After a test vehicle had been driving at low speeds, grass readily ignited when positioned between the catalytic converter and heat shield. A set of laboratory experiments applied standing and cradled ('about the size and shape of a cupped hand') dry grass samples to various temperatures of a section of exhaust pipe. Samples contained between zero and 11% MC. Ignition depended on sample size, compaction, wind speed, and exhaust pipe temperature. At exhaust pipe temperatures above 425ºC flaming ignition always occurred for cradled samples, but standing samples required at least 525ºC for ignition (Knight & Hutchings, 1987).

Table 2.2 Summary of experiments investigating fire ignition from hot metal contact.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold	Reference
Environmental chamber tests involving four different fuel types to investigate ignition temperatures from hot chainsaw mufflers	Hot chainsaw muffler	Punky (decayed) wood (2 mm particle size), cheat grass (up to 7.6 cm long), mahogany wood sawdust (0.3 cm particle size), tree moss (0.2 cm particle size)	Conclusions suggest that no ignitions will occur if muffler temperature ≤ **260ºC** and exhaust temperature ≤ **232ºC**. This is true for low RH and ambient temperature up to 35.6ºC.	Kaminski 1974
Laboratory experiments investigating ignition temperatures and time-to-ignition for common outdoor fuels. Ambient temperature was 20ºC and RH < 50%	Hot metal copper plate (10.2 x 10.2 cm)	May tall fescue (not cured), 0.034 g/cm^2	Flaming only occurred 11% of the time, glowing ignition occurred for all other times. With wind speed at 2.5 m/s, ignition began at **310ºC**, without wind speed, ignition began at **340ºC**	Pitts 2007
		August tall fescue (cured), 0.027 g/cm^2	Flaming only occurred with wind, glowing ignition occurred with or without wind. With wind speed at 1.0 m/s, ignition began at **310ºC**, without wind speed, ignition began at **371ºC**	
		Cheat (cured), 0.031 g/cm^2	Flaming only occurred with wind, glowing ignition occurred with or without wind. With wind speed at 2.5 m/s, ignition began at **350ºC**, without wind speed, ignition began at **380ºC**	
		Fine Florida grass (cured), 0.031 g/cm^2	Flaming occurred with wind, and once without wind, glowing ignition was most common without wind. With wind speed at 1.0 m/s, ignition began at **310ºC**, without wind speed, ignition began at **320ºC**	
		(Samples contained 10 - 14% MC and were put in a wire cage to 2.5 cm depth)		
Bunched dry grass applied to various temperatures of a section of exhaust pipe. Ambient temperature was 16 to 19ºC, RH was 43 to 69 %, wind speed varied between 1.0 and 1.5 m/s	Hot exhaust pipe	Bunched dry grass at 0% MC, held in hand when applied to exhaust pipe (vertical orientation), and grass held in a cradled orientation	No ignitions at less than **481ºC** but ignitions observed at **525ºC** (vertical orientation), no ignitions at less than **400ºC** (cradled orientation)	Knight & Hutchings 1987

2.3.2 Hot Carbon Emissions (carbon emissions and gas from vehicle exhausts)

Hot carbon particles are produced during normal vehicle operation (Davis *et al.*, 1999; DeHaan, 2002; Babrauskas, 2003; Bosch, 2004). Excess carbon is usually produced when vehicles are in idle, are operating at low power, or are poorly maintained, which increases the potential for hot carbon to flake off the exhaust pipe and exit the tailpipe as hot sparks (Davis *et al.*, 1999). Carbon is usually expelled from the tailpipe or manifold during high revving, gear shifting (especially down shifting), and high throttle use. Carbon particle sizes can range from microscopic to over 10 mm in diameter (San Dimas EDC, 1980; Babrauskas, 2003). Fire records from 1975 to 1979 cited that over 39% of equipment-caused fires in California were caused by exhaust sparks (McCurnin, as cited by Babrauskas, 2003).

A Californian fire prevention guide indicated that some vehicles can eject flaming carbon particles from the exhaust system, which is a dangerous fire risk (Davis *et al.*, 1999). For example, the incidence of catalytic converter meltdown can cause multiple fires from one vehicle. This can happen to new or old vehicles, and is caused by a malfunction within the electronic ignition system. Raw fuel enters the exhaust system and the catalytic converter becomes a combustion chamber. Next, melted pieces of the catalytic converter are ejected from the tailpipe at temperatures over 1000ºC. This has been described as “fuses being thrown out of the vehicle,” or “a steady stream of fire coming out of the exhaust system” (Davis *et al.*, 1999, p. 135). Over an 11-year period, the Shasta-Trinity region of California experienced 29 fires that burned almost 300 ha due to catalytic converter meltdown incidents (Davis *et al.*, 1999). Only 33% of vehicles that caused the fires were found. This implied that the malfunction can rectify itself, and allow the vehicle to continue to run without problems.

New Zealand legislation restricts the operation of spark-hazardous engines in rural areas (Forest and Rural Fires Act 1977, 2008). It is the user’s responsibility to ensure dangerous sparks or flames do not exit the vehicle. Spark arresters trap particles larger than 0.58 mm in diameter, and mufflers, superchargers, and catalytic converters are not effective spark arresters (Gonzales, 2003a; 2003b). Furthermore, spark arresters do not function properly if they are not maintained. Although it is not mandatory in New Zealand, the use of spark arresters does reduce fire risk from hot carbon emissions. Without spark arresters, hot carbon particles can escape from exhaust systems at temperatures up to about 870ºC and diameters up to 12.7 mm (San Dimas EDC, 1980).

Ignition probability from hot carbon has not been widely studied, and experimental design can be difficult due to heat transfer mechanisms between hot carbon particles and the fuel source (Maxwell & Mohler, 1973; DeHaan, 2002; Babrauskas, 2003). Hot carbon and grass fuels have similar surface roughness properties, but hot carbon particles are much smaller than grass fuels. Thus, hot carbon exhibits low contact force when it lands on grass. Contact is only through spikes and ridges, rather than the entire surface of the particle and the grass fuel. Therefore, the probability of ignition is influenced by the probability of carbon particles landing on fuel in a favourable position. This is difficult to achieve in an experimental design.

Exhaust gas can reach 900ºC when entering the exhaust system at the manifold. However, this temperature is greatly reduced as gas flows through to the tailpipe. Typical temperatures at the tailpipe are 100 to 200ºC in idle, and 550 to 800ºC at maximum output (Heisler, 1999; Bosch, 2004; Gonzales, 2008). Tests recorded exhaust gas temperature of a Buda Lanova diesel engine, used in industrial machinery and trucks, from 150 to 555ºC for workloads between idling and 1200 RPM (Maxwell & Mohler, 1973). Babrauskas (2003) states that lawnmowers produce exhaust gas temperatures up to 370ºC.

Gonzales (2008) reported that exhaust gas temperature is considerably higher on diesel trucks equipped with a DPF (368ºC) compared with trucks without a DPF (202ºC) (Table 2.1). These temperatures were measured just outside the tailpipe. Dead cheat grass at 30% MC was placed in direct contact with the exhaust gas for five to ten minutes. The grass smoked and browned, but did not ignite. Ambient temperature was between 15 and 21ºC and RH was 60 to 64%. The report by Gonzales (2008) contained useful information about exhaust gas and surface temperatures, but further work is needed to increase confidence in the ignitibility of dead cheat grass and other grass species from exhaust gas.

Maxwell and Mohler (1973) conducted 186 tests where hot carbon particles between 1.5 and 2.0 mm in diameter were dropped onto flats of cheat grass. Three tests resulted in flaming ignition, and 12 produced glowing or smouldering ignition. Two recommendations were reported: 1) particles larger or equal to 1.5 mm in diameter can glow for at least 30 seconds, and sometimes up to one minute; and 2) there is a high risk of ignition from exhaust particles within eight metres of the particle origin. San Dimas EDC (1980) completed tests involving particles with a diameter from 2.29 to 9.91 mm that were scraped from diesel and petrol exhausts. Their results agreed with Maxwell and Mohler (1973), and suggested that carbon particles can be ejected up to 14 m from the exhaust system. The particles were also found to ignite cheat grass, sawdust, and punky wood. The cheat grass burned rapidly, whereas punky wood smouldered for over two hours before flaming. Kaminski (1974) suggested that ignition of cheat grass does not occur if chainsaw exhaust gas remains below 232ºC.

2.3.3 Metal Sparks

Metal sparks are generally produced by grinding or cutting operations through use of power tools. Trains have also been reported to cause sparks (as detailed in Table 2.9). Sparks exhibit the same heat transfer properties as do hot carbon particles, where only parts of the spark and fuel contact each other, decreasing the probability of ignition (DeHaan, 2002). Therefore, sparks must land on fuel in a favourable position for ignition to occur.

Little information about the ignition potential of metal sparks was found in the literature. Babrauskas (2003) maintained that the size of welding splatter particles varies widely. Many particles are below 1.0 mm in diameter, but some can be between 1.0 and 3.0 mm. Sawdust ignited within one second (from 1.5 mm particles) and wood shavings within four to five seconds (from 1.9 mm particles). DeHaan (2002) reported that metal sparks are a significant ignition source, and can be produced by welding splatter, grinding operations, saws, and other power tools. Lawnmowers also produce sparks if they hit rocks or other hard objects, posing significant ignition risk to dry roadsides or other grass areas (Babrauskas, 2003).

2.3.4 Organic Embers

If organic material is extremely hot, smouldering, or flaming it can be a significant ignition source. One type of organic ember is produced by accumulated debris on vehicles. For example, 4WD vehicles or machinery can trap mud and grass on hot parts of the exhaust or braking systems. It is possible for the hot organic material to fall off and ignite grass fuels. Burning cigarettes are another common type of organic ember, and can reach temperatures between 600 and 700ºC, depending on the brand (Redsicker & O'Connor, 1997; Steensland, 2005). This section reviews ignitions from accumulated debris on hot vehicle parts, and from cigarettes.

Baxter (2004) carried out experiments using two ATVs that were sunk into muskeg vegetation of mucky consistency to accumulate organic material around the operating system. They were then driven for eight minutes in an ambient temperature of 15ºC. By this time, the accumulated vegetation had dried and begun smouldering at several points along the exhaust system. Within 15 minutes the smouldering vegetation began dropping onto the ground. Baxter (2004) also conducted a survey of ATV riders, and 52% of respondents reported that they had smelt burning from their own or another person’s ATV.

The ignition risk from cigarettes is commonly misinterpreted. The NRFA recorded that only 1% of New Zealand’s wildfires (1991-2007) were caused by cigarettes, and this only contributed to 0.2% of New Zealand’s grass fires (Doherty *et al.*, 2008). Galtié (2006) reported that ignitions from cigarettes are much easier to achieve in controlled laboratory conditions, with low likelihood of occurring in a natural environment. Redsicker and O'Connor (1997) suggested that fires caused by cigarettes are subject to three elements, each with decreasing likelihood: 1) the burning cigarette and fuel must be in contact; 2) the fuel source must be in a state favourable for ignition; and 3) the cigarette's position must be inclined to ignite the fuel. Furthermore, ignition probability depends on the smoker's character. The smoker must discard the cigarette carelessly for it to be a potential ignition source.

The NRFA (2007) provides fire investigators with an indication of conditions which are conducive to cigarette fires (Table 2.3). For ignition to occur, ambient temperature must be high, RH must be less than 22%, and wind speed must not be too fast or too slow. An ideal wind speed of 1.3 m/s has been reported (Countryman, 1983; Steensland, 2005). Furthermore, dead fuel MC must be less than 14%. Research indicated that ignitions are more likely to occur if fuel arrangement is horizontal, fuel moisture is low, fuel is cured, fuel density is high, and fuel particles are small (Sale & Hoffheins, 1928; Countryman, 1983; Redsicker & O'Connor, 1997; Galtié, 2006; National Rural Fire Authority, 2007). Once these criteria are met, the cigarette must land in the fuel at the correct orientation. Ford (1995) maintains that at least a third of the cigarette must contact the fuel for ignition to occur. Moreover, when cigarettes burn, ash surrounds the ember where glowing combustion is taking place. This ash acts as a buffer between the ember and the fuel, further decreasing ignition probability (Steensland, 2005).

Table 2.3 Indicators for wildfires caused by smoking cigarettes (from National Rural Fire Authority, 2007).

Cigarette Caused Fires
PROBABILITY OF IGNITION BASED ON RELATIVE HUMIDITY
Fuel conditions critically dry:
RH less than 22% and fine dead fuel moisture less than 14%.

Start Likely	Start Possible	Start Unlikely	No Start
0% RH	10% RH	18% RH	22 % RH

Sale and Hoffheins (1928) determined the probability of dry grass ignition from various brands of cigarettes and cigars (Table 2.4). Cigarettes and cigars were lit and placed into a wire cage full of dry grass at MC < 12%. Without wind, no ignitions occurred, but as wind speed increased so did ignition probability. At 2.8 m/s, the probability of ignition was 50% for a grass bed of 0.043 g/cm^3 density. This increased to 80% for a grass bed of 0.099 g/cm^3 density. Ignition probability of cigars was about half that of cigarettes, and did not increase any further when wind speed was increased. This was probably because cigarettes contain an additive that aids in glowing combustion, whilst cigars do not (Redsicker & O'Connor, 1997). Ignition times varied between five and 11 minutes, where higher wind velocities were conducive to faster ignition times (Sale & Hoffheins, 1928).

Countryman (1983) investigated the ignitibility of dead cheat grass (*Bromus tectorum* L.) from cigarettes (Table 2.4). Tests were conducted in a controlled chamber at 27ºC, with a 1.3 m/s wind speed. RH was varied to condition grass samples to different MC values. Samples included three size classes based on grass length, fine (< 0.3 cm), medium (0.3 to 0.5 cm), and coarse (1.9 to 3.8 cm). Cigarettes were placed onto the samples at three orientations, towards the wind, at right angles to the wind, and away from the wind. No ignition occurred for coarse fuel. Some ignitions and many marginal ignitions occurred for medium fuel, but no clear trends were observed. The ignition threshold for fine fuel suggested that ignition occurs below 14% MC. Deeper fuel beds increased the probability of ignition slightly. The study reported that when facing towards the wind, the probability of ignition from a burning cigarette was higher compared with other orientations. The results from this study indicated that the likelihood of cigarettes igniting long grass in its natural environment is low (Countryman, 1983).

Table 2.4 Details of experiments investigating fire ignition from cigarettes and cigars.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold or Probability	Reference
Laboratory experiments using cigarettes and cigars to test the ignition probability of dry grass (< 12% MC)	32 mm long burning cigarettes (filter or non-filter types), and various lengths of burning cigars	Dry grass stuffed into 2.5 cm high wire cages (density was 0.032 - 0.099 g/cm^3)	For cigarettes with grass at 0.043 g/cm^3 density: 0% for 0.7 m/s 5% for 1.4 m/s 30% for 2.0 m/s 50% for 2.8 m/s If wind increased above 2.8 m/s ignition probability did not increase, but if grass density increased to 0.099 g/cm^3, ignition probability became 80%, Ignition probability was about half for cigar tests	Sale & Hoffheins 1928
Experiments conducted in a controlled chamber to test the ignitability of dead cheat grass from burning cigarettes	50 mm long burning cigarettes	Dead cheat grass sorted into 3 density classes based on length: fine (< 0.3 cm), medium (0.3 - 0.5 cm), and coarse (< 3.8 cm), round containers were 6 or 13 mm deep with a 7.6 cm diameter	Conditions were 27ºC and 1.3 m/s wind speed. Fine fuel: **< 13.5% MC**, Medium fuel: no clear trend, but can assume with confidence < **14% MC**, Coarse fuel: No ignition at any MC	Countryman 1980

Babrauskas (2003) noted that when dried cow dung is pulverized by cow hooves, it can be ignited by cigarette butts. Once ignited, the fire may spread to surrounding grassland.

2.3.5 Open Flame

Flames are generally categorised into two types (diffusion and premixed), but sometimes exhibit characteristics of both (partially premixed) (Johnson & Miyanishi, 2001). Diffusion flames are caused when fuel and oxygen (or other oxidiser) are separate before ignition, such as open flames from wildfires, camp fires, solid fuel cookers, matches, and candles (Johnson & Miyanishi, 2001; DeHaan, 2002). Premixed flames are caused when fuel and oxygen are mixed before ignition, such as open flames from drip torches, ordinary or wind-proof liquid-fuel lighters, and backcountry and camping gas or liquid fuel cookers. Flame temperatures range from about 500 to 1400ºC, where flames with lower temperatures are dark red, and flames with higher temperatures are yellow to bright white (Redsicker & O'Connor, 1997; DeHaan, 2002). The open flame ignition sources mentioned below are generally between 900 and 1400ºC (DeHaan, 2002; Babrauskas, 2003). Open flame can ignite fuels easily due to its ability to dry fuel.

Eleven types of litter from Australian shrubs and trees were tested by a range of piloted open flame ignition sources (aerial incendiaries and cotton balls dipped in methylated spirits) to investigate factors influencing ignition thresholds (Plucinski & Anderson, 2008). Variables included litter type, ignition source, MC, and wind speed. Logistic regression was used to model the probability of ignition for different fuel MC levels. Main conclusions suggested four major trends:

1) litter types have different surface area-to-volume ratios and different densities, which explains different observations for litter success;
2) fuels with higher MC can be ignited more readily at low densities compared with higher densities;
3) fuels with higher MC ignite more readily by large ignition sources compared with small ignition sources; and
4) if the ignition source is located above the litter, wind decreases the probability of ignition; however, when the ignition source is located within the litter, the opposite occurs.

Over the course of a year, a drip torch was used to investigate the ignitibility of slender oat at different stages of its life cycle in Greece (Dimitrakopoulos *et al.*, 2010). There was a wide range of ambient temperatures and RH. Wind speed varied from 0 to 11.1 m/s. Ignition thresholds were modelled by a highly significant logistic regression model which predicted a 50% probability of ignition at grass MC of 38.5% (Table 2.5).

Table 2.5 Details of experiments investigating ignition from open flame.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold	Reference
188 field test fires to create a model to predict probability of ignition. Ambient temperature 8 to 35ºC, RH 21 to 93% and wind speed 0 to 11.1 m/s	A 10 m long ignition line started with a drip torch (1:1 diesel/petrol mix)	4000 m^2 area covered by the grass species *Avena barbata* Pott. ex Link. Tests took place over an entire year, with no indication of grass length, MC ranged from 8 to 114%	A highly significant logistic regression model predicted that a 0.5 probability of ignition occurs at **38% MC**. No ignitions occurred above **41.5% MC**.	Dimitrakopoulos *et al.* 2010
Laboratory experiments to test how moisture content affects ignitability of slash pine litter	Burning wooden matches (small, regular and 3 regular stuck together)	Slash pine litter conditioned to various moisture contents	Small: **25% MC**, Regular: **30% MC**, and 3 regular bound together: **40% MC**	Blackmarr (as cited by Alexander 1991)
Laboratory experiments to test the ignition thresholds of dead and live grass from flamming matches, no wind	Flaming matches: one randomly dropped onto sample from ~ 10 cm, if no ignition within 2 min, another was dropped, a third match was dropped if no ignition occurred from the second	Dead and live *Imperata cylindrica* grass (10 cm length, and 30 g (fresh weight) per sample), conditioned to 5% increments of MC ranging from 5-70%, tested in 15 cm diameter piles	Dead grass - **35% MC**, probability of ignition 50% Live grass - **28% MC**, probability of ignition 50%	de Groot *et al.* 2005

Blackmarr (1972), determined the ignition probability of slash pine litter from different sizes of flaming matches (Table 2.5). A 'critical range' of MC, where ignition reverted from 100 to 0%, was determined for each match size. These MC ranges were: 16 – 25% for small sized wooden matches, 18 – 30% for regular sized wooden matches, and 24 – 40% for three regular sized wooden matches bound together. These results indicate that as firebrand size increases, the ignition probability of slash pine litter increases, especially at higher MC values.

Ignition probability from flaming matches was modelled for live and dead kunai grass (*Imperata cylindrica*) in Indonesia (de Groot *et al.*, 2005). A positive test result occurred if a fire larger than 50 cm^2 developed within two minutes of dropping a flaming match. If this did not happen, the process was repeated a maximum of two more times. A negative result was recorded if a fire had not developed according to the aforementioned criteria. The ignition threshold ranges for dead and live grass were determined to be 31 – 40% and 11 – 44% MC respectively (Table 2.5).

2.4 Other Significant Ignition Sources

2.4.1 Spotting

Spot fires usually occur from flaming or glowing firebrands. Ignition from spotting is related to ignition from organic embers. The following review is an extension of subsection 2.3.4 because literature for organic ember ignition sources was limited.

During a wildland fire, firebrands are commonly launched from burning trees or scrub, posing significant fire risk to surrounding areas, especially grasslands (Pyne *et al.*, 1996; Tolhurst & Cheney, 1999; Gould *et al.*, 2007; Cheney & Sullivan, 2008; Sardoy *et al.*, 2008). This mechanism can cause spot fires at distances many kilometres from the fire front (in extreme cases). Models have been developed to predict the distance that firebrands can be launched, depending on certain conditions (Albini, 1979; 1983; Ellis, 2001). However, they did not predict the likelihood of fuel ignition when the firebrand reached the ground. The model predicted that the maximum spotting distance for a fire in short, flat grassland, with a fire intensity of 2000 kW/m and wind speed of 5 m/s at 10 m, was 260 m (Albini, 1983). This distance varied with burning fuel-type, topography, wind speed, and other factors. Albini (1983) reported that in rare cases, spotting can occur over two kilometres away.

Clements (1977) tested maximum velocity of non-burning firebrand-types, including bark, leaves, moss, pine cones, and needles. Results recorded that speed ranged from 1.3 to 16.5 m/s. Maximum flaming and glowing firebrand times were also investigated, where flaming and glowing can last for up to 1.2 and 13.5 minutes respectively.

Grazed grassland and farmland is commonly littered with cow dung. When cow dung ignites from embers or firebrands, fire can easily spread to surrounding grassland. At RH of 50% and 15ºC ambient temperature, non-flaming firebrands (up to 2.0 x 0.5 cm in size) ignited dried cow dung at less than 11% MC (Table 2.6) (Bunting & Wright, 1974). The ignitibility of decayed wood from non-flaming firebrands was also tested, and no ignitions occurred above 15% MC. Cow dung and decayed wood ignitions were possible at RH up to 85%, with temperatures as low as 4.4ºC. Another study indicated that ignitions were possible with firebrands 0.3 x 1.5 cm when dried cow dung contained less than 13% MC (Babrauskas, 2003).

In a laboratory, several fine fuels were tested for ignition probability using small ponderosa pine firebrands, called embers. Pine needles and shredded paper (11% MC) ignited from flaming embers that were 25 mm diameter and 8 mm thick (Manzello *et al.*, 2005). Single glowing embers ignited shredded paper, and large (50 mm diameter and 6 mm thick) multiple glowing embers ignited pine needles at wind speed of 1.0 m/s (Table 2.6). Manzello *et al*. (2006) expanded on the previous study to test shredded hardwood mulch, pine straw mulch, and cut grass (Table 2.6). No samples ignited from glowing embers. All samples ignited from one flaming ember at 0% MC. Pine straw also ignited from one flaming ember at 11% MC. Grass ignited at 11% MC from four flaming embers. Another study investigated the behaviour of firebrands using a firebrand generator in the field but did not include grass samples (Manzello *et al.*, 2008). Conclusions suggested that the generator successfully represented firebrands of burning trees, and that firebrands were launched up to a 6.3 m horizontal distance away.

McArthur (1966), Pérez-Gorostiaga *et al.* (2002) and Guijarro *et al.* (2002) all found that dead grass ignited more readily than other fuels. Curt *et al.* (2007) reported that there was little difference in ignition behaviour between live grasses and other vegetation types, unless the grass was mixed with other litter types (Table 2.6). Pérez-Gorostiaga *et al.* (2002) found that in still conditions, dead Mediterranean grass readily ignited from several types of flaming firebrands including pine cones, bark, leaves, and twigs; but in most cases there was less than a 10% ignition probability from glowing firebrands for a 0.8 m/s wind speed.

Table 2.6 Details of experiments investigating ignition from flaming and glowing firebrands.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold or Probability	Reference
Laboratory and field experiments, using non-flaming firebrands to test the ignitability of dry cow dung (cow chips) and decayed (punky) wood	Non-Flaming Juniper Firebrands: Small 1.0 x 0.2 cm Medium 1.5 x 0.3 cm Large 2.0 x 0.5 cm	Cow Chips	11% MC in the following conditions: 15ºC, 50% RH, and 2.68 m/s	Bunting & Wright 1974
		Punky Wood	< 15% MC in any environmental condition	
Laboratory experiments to test the possibility of ignition from flaming and glowing embers which had been manufactured from *Pinus ponderosa* (ponderosa pine)	Flaming and glowing ponderosa pine disks, small: 25 mm diameter, 8 mm thick, and large: 50 mm diameter, 6 mm thick	Pine needles and shredded paper at 0 to 11% MC, in separate 23 x 23 x 5.1 cm aluminium foil beds	Conditions were 21ºC and 3 wind speeds (0, 0.5, and 1.0 m/s). The following results are for 11% MC. Shredded paper ignited from a single glowing ember, and pine needles ignited from large multiple glowing embers at 1.0 m/s. All samples ignited from a single flaming ember.	Manzello *et al.* 2005
Laboratory experiments to test the possibility of ignition from flaming and glowing embers which had been manufactured from *Pinus ponderosa* (ponderosa pine)	Flaming and glowing ponderosa pine disks, small: 25 mm diameter, 8 mm thick, and large: 50 mm diameter, 6 mm thick	Shredded hardwood mulch, pine straw mulch, and cut grass at 0 to 11% MC, in separate 23 x 23 x 5.1 cm aluminium foil beds	Conditions were 21ºC and 2 wind speeds (0.5 and 1.0 m/s). All samples ignited from one flaming ember at 0% MC. Pine straw ignited from one flaming ember at 11% MC. No samples ignited from glowing embers. Grass ignited at 11% MC from four flaming embers.	Manzello *et al.* 2006

Table 2.6 Details of experiments investigating ignition from flaming and glowing firebrands, cont.

Experiment Description	**Ignition Source**	**Sample Type**	**Ignition Threshold or Probability**	**Reference**
Laboratory experiments to test ignition probability of several Mediterranean fuel beds from firebrands	16 different types of glowing and flaming firebrands ranging from twigs, bark, leaves, cones, and scales of *Pinus*, *Quercus*, and *Eucalyptus* species	A range of pine needles, eucalyptus leaves, and dry dead grasses at various MCs, in separate 22 x 16 x 2.5 cm aluminium trays	No indication of the ambient temperature or RH. Wind speed was 0, 0.8, 2.5, and 4.5 m/s. Logistics regression was used to produce models to predict ignition probability. Dead grasses had a higher ignition probability from flaming firebrands and no wind compared with other fuel types. On the other hand, ignition probability was less from glowing firebrands with wind.	Pérez-Gorostiaga *et al*. 2002
Laboratory experiments to test ignition behaviour of Southern-European woody species and grasses	Flaming and glowing *Pinus sylvestris* cubes 2 x 2 x 1 cm in size, at 12% MC when lit by an electric radiator	Litter beds of 8 woody species, and 2 types of dead grass collected in tufts between 10 and 50% MC	Grass species had lower time-to-ignition values, higher rate of spread and combustion, and higher flame length than the woody species. The denser grass species also had lower time-to-ignition values, and higher rate of spread etc. Successful grass fuels ignitions occurred for MC values up to 43%, and occurred within 2 seconds of exposure to the ignition source.	Guijarro *et al.* 2002
Laboratory experiments to test flammability of Southern France vegetation commonly found on roadsides, tested with two wind speeds (1 and 2.9 m/s)	Flaming and glowing Pinus sylvestris cubes 2 x 2 x 1 cm in size, at 12% MC when lit by an electric radiator	Grass samples consisted of a variety of dicot grasses (*Festuca* spp., *Dactylis* spp., *Lolium perenne*, *Lotus corniculatus*, *Sanguisorba minor*, and *Plantago lanceolata*) and Graminae grasses (*Brachypodium* spp., *Festuca* spp., and *Dactylis* spp.). Three other sample types were also tested including pine litter (*Pinus halepensis* needles), litter + grasses (pine litter, oak leaves and graminae grasses), and litter + grasses + shrubs (pine litter, oak leaves, shrub (*Quercus coccifera*) leaves and twigs, and graminae grasses). Samples were collected and tested in two different arrangements: unmanaged, and mowed, with MC up to 75% for fresh specimens, oven-dried MC was not reported	In most cases lower MC values increased ignition probability. Grass + litter ignited more readily than other mixes, and mowed samples ignited more readily than unmanaged samples. Successful ignition occurred for almost all cases using the flaming cube. Successful ignition was low with a wind speed of 1 m/s and a glowing cube, but was high with a wind speed of 2.9 m/s. Time-to-ignition could not be predicted due to variability in the data.	Curt *et al.* 2007

Guijarro *et al.* (2002) and Curt *et al.* (2007) used the same firebrand type for experiments that compared ignition behaviour of Southern-European and Southern-France vegetation respectively (Table 2.6); but Curt *et al.* (2007) used glowing in addition to flaming firebrands. Within two seconds all dead grass samples were found to ignite at MC values up to 43%, and grass samples with higher density exhibited a higher percentage of ignitions (Guijarro *et al.*, 2002). Grass mowing did not reduce ignition probability at roadsides compared with unmanaged grasses, and ignitibility was higher in mowed grass when exposed to a glowing firebrand (Curt *et al.*, 2007). Curt *et al.* (2007) also determined that time-to-ignition could not be predicted, due to the variability in the ignition behaviour of samples.

2.4.2 Hot Air/Gas Ignition Sources

Several apparatuses can be used to measure ignition thresholds by hot air or gases. These include ovens (Babrauskas, 2003), the cone calorimeter (Babrauskas & Parker, 1987; Babrauskas, 2003), the ISO 5657 ignition apparatus (Babrauskas, 2003), and the muffle furnace (Gill & Moore, 1996). This section reviews work done by various researchers on ignition by hot gases.

Bowes (as cited by Babrauskas, 2003) used a crossing-point technique and determined that the ignition temperature of grass at 6% MC is 249ºC. This is the lowest temperature reported of all the studies reviewed. This technique involved placing the fuel sample together with a thermocouple into an oven, then slowly increasing the oven temperature. When the temperature of the thermocouple exceeded that of the oven, it was reported as the 'critical temperature,' which is generally the charring or pyrolysis temperature rather than the flaming ignition temperature (Babrauskas, 2003).

Using hot air flow from an ignition apparatus approved by ISO (5657-1986E, revised as ISO 5657, 1997), significant regression models were developed for the leaves of 25 and 17 species of Mediterranean plants (Dimitrakopoulos & Papaioannou, 2001; Dimitrakopoulos *et al.*, 2006 repsectively), with twelve species common to both studies. These models can be compared with other studies that used International Standards Organisation requirements for ignition testing (ISO 5657, 1997). Leaves of some shrub and tree species contain higher levels of essential oils than grass species, and can sustain burning at MC values of up to 140%. However, less flammable leaves may not sustain burning at MC values over 50% (Dimitrakopoulos & Papaioannou, 2001).

The flammability of dry (7% MC) straw beds was tested by convective heating at various temperatures and air flows (Di Blasi *et al.*, 1999). Flaming ignition was observed at 276ºC with air flows of 1.9 m/s (Table 2.7). This ignition temperature increased as air flow decreased, resulting in flaming ignition at 376ºC at air flows of 0.35 m/s. Time-to-ignition decreased as temperature and air flow increased. Stockstad (1976) used a furnace ignition source and reported that dead cheat grass containing 18% MC spontaneously ignited above 440ºC, and that ignition occurred above 370ºC with a pilot source (Table 2.7).

Table 2.7 Summary of experiments investigating hot air as an ignition source.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold	Reference
Laboratory analysis investigating flammability of straw beds (at 7% MC and 50 kg/m^3), using convective heating	Hot air ranging from 266 - 617ºC with flow rates ranging from 0.35 - 1.9 m/s	Untreated and rain-leached straw beds	Flaming ignition for untreated straw occurred at **376ºC** at air flow rates of 0.35 m/s, and **276ºC** at air flow rates of 1.9 m/s. Values are slightly higher for rain-leach straw. Ignition times were found to decrease as temperature was raised.	Di Blasi *et al.* 1999
Laboratory experiments investigating ignition temperatures and time-to-ignition of cured grass (no wind speed and no indication of RH)	Furnace set to various temperatures	Cured cheatgrass (*Bromus tectorum* L.) of 0.14 cm diameter and 2.54 cm length (5.4, 10.1, or 18.6 % MC)	Spontaneous: **440-460ºC** for all MCs Piloted: **370-390ºC** for all MCs	Stockstad 1976

2.4.3 Glass

Glass has been reported as a potential ignition agent for wildland fuels (Babrauskas, 2003; Cheney & Sullivan, 2008). The 'burning-glass effect' is known as the ability for biconvex lenses to focus the sun's rays to heat anything present in the focal point. Wittich and Müller (2009) conducted field experiments with five different bottle types and six different fuel types, and found that no ignition occurred over 21 days of testing. They concluded that naturally heated glass is highly unlikely to ignite grass containing over 5% MC (Table 2.8). Wittich and Müller (2009) also report that no other studies found wildland fuel ignitions for any experiment containing glass pieces. Limited ignitions were observed using magnifying glasses and glass containers filled with water (Fuquay and Baughman, Wittich and Lex, Müller, *et al.* as cited by Wittich & Müller, 2009). Little research has been conducted on this topic, and the belief that ignitions are likely from glass bottles or fragments is probably often misconstrued.

Table 2.8 Summary of an experiment investigating glass as an ignition source.

Experiment Description	Ignition Source	Sample Type	Ignition Threshold	Reference
Laboratory and field experiments to analyse the ignitability of litter beds involving 5 types of glass bottles as ignition sources	Glass bottle fragments and the sun, ambient temperature range was 16.7 - 35.3ºC	Various littler beds including beech leaves, spruce and pine needles, heather, and 2 grass types (*Avenella flexuosa* and *Calamagrostis epigejos*)	Charring occurred at **327ºC** from ketchup-bottle bottom, but no ignitions occured from any bottle. Ignition is highly unlikely to occur from glass bottles if fuel moisture content is over 5%.	Wittich & Müller 2009

2.4.4 Power Lines

Power lines are considered to be a potential ignition agent, especially when they are present in grassland areas (Babrauskas, 2003; Cheney & Sullivan, 2008). They can produce metal sparks by rubbing together in high winds or falling over. Burning embers can be produced from rubbing against trees, which fall to the ground and ignite surface fuels.

A theoretical study considered the ignition probability of dry grassland fuels from three high-wind scenarios: 1) hot copper particles (≤ 2 mm diameter) from arcing power lines, 2) burning aluminium sparks (≤ 2 mm diameter) from arcing power lines, and 3) burning embers or firebrands (≤ 20 mm diameter) caused by high voltage power lines contacting trees (Tse & Fernandez-Pello, 1998). Results indicated that small copper and aluminium sparks less than 1.5 mm diameter would probably burn out before reaching the ground; however, copper has a high heat conducting capacity, and does have the potential to reach the ground at a high temperature. Aluminium sparks 1.5 mm in diameter and larger had the potential to reach the ground in a burning state. Firebrands also had the potential to reach the ground in a burning state if they were above 2 mm in diameter. Wind was predicted to carry aluminium sparks farther than copper sparks of the same size, but not as far as firebrands of the same size. Firebrands were found to have the potential to ignite grass fuels long distances away from power lines.

Rallis and Mangaya (2002) suggested that there is high probability of ignition from hot aluminium particles produced by clashing overhead transmission lines in South Africa. Experiments involved dry veld grass and indicated that ignition occurred at temperatures as low as 300ºC. Results suggested that particles less than or equal to 5.6 mm diameter travelled over 10.7 m and landed in grass fuels at temperatures exceeding 300ºC.

Stokes (1990) completed a variety of experiments investigating the risk of ignition from electrically-produced steel, aluminium, and copper droplets. Steel and aluminium droplets were found to pose a severe fire risk to grassland fuels. Conversely, copper particles posed little risk to grassland fuels, as they frequently broke up into very small particles. No particles < 1 mm diameter ignited barley grass. These conclusions agree with the theoretical study by Tse and Fernandez-Pello (1998).

2.4.5 Self-heating

Hay (from various grass species) and esparto grass (*Stipa tenacissima* and *Lygeum spartum*) have the ability to self-heat under moist conditions (Rothbaum, 1964). For example, when RH is about 96% self-heating of esparto grass occurs. This turns into chemical heating, thereby increasing the chance of spontaneous ignition. This occurs between 66 and 71% RH for hay

(Rothbaum, 1964). Self-heating does not normally propagate into flaming fires, but instead, fuel slowly smoulders from the inside out.

2.4.6 Miscellaneous Ignition Sources

It is possible for grass fires to start from conductors on electric fences (Babrauskas, 2003). Another source is muzzle-loading firearms, which are usually used for target shooting, hunting, and historical re-enactments. They have the potential to ignite forest fuels under extreme weather conditions, such as temperatures over 32ºC combined with RHs under 20% (Haston *et al.*, 2009).

2.5 Brief Overview of Grass Fires in Canterbury

From 1991 to 2007 an average of 553 wildland fires were recorded in Canterbury each year (Doherty *et al.*, 2008). Although about 13% of these fires were caused by unknown sources, 99.9% of fires caused by known sources were attributed to human activity. A review of fires including their ignition causes follows, where tussock and other grasses were the predominant fuels burned (Table 2.9). This review contains a summary of 25 significant reports for Canterbury from 2003 to 2009, in which the majority of ignition causes were from trains that expulsed hot metal or from vehicles. Metal sparks, fireworks, and power lines were among the other causes. Even though, it is common for fires to be started by mowers, documentation for these fires is rare (Barnes, personal communication, December 16, 2009). Fire sizes ranged from < 0.01 to 52 ha, ambient temperatures from 8 to 31.5ºC, RH from 11 to 80%, and wind speed from light breezes (1 m/s) to 35 km/h (10 m/s). The Poyntz Road, Miners Road and Lake Emma fires are particularly significant to this research because they burned in highly cured grass fuels, with low RH and relatively high ambient temperatures. Furthermore, they were caused by hot vehicle parts:

- At 12:25 PM on January 7, 1999, a fire burned approximately 34 ha of long cured grass and pasture on the east side of Poyntz Road, in the Ashley Rural Fire District (National Rural Fire Authority, 1999). The fire cause was determined to be a hot piece of metal that had been expelled from the exhaust system of a loaded transporter. Ambient temperature was about 23°C, RH was 32%, and wind speed was high, ranging from 37 to 70 km/h.

- On the afternoon of February 2, 2003, a fire burned almost 200 ha of flat grassland and pine plantation on the outskirts of Christchurch, next to Miners Road (Anderson, 2003). The ignition cause was attributed to a vehicle turning around at the north end of the road. Either the catalytic converter or another part of the hot exhaust system came into contact with grasses cured to around 88%, heating them to their ignition point. Ambient temperature was about 23ºC, relative humidity (RH) ranged from about 24 to 53% and wind speed varied between 9 and 30 km/h.

- On the afternoon of March 24, 2007, the Lake Emma fire burned 27 ha of the Mt. Harper Conservation area, 3.5 km south of Lake Clearwater Village, or about 30 km inland of Mt. Somers township (Taylor, 2007). This was caused by the hot exhaust system of a Honda XR 400R trail bike, which was fitted with a spark arrester. The trail bike rider was trying to ride up a steep area, but he fell off his bike several times. The last time he fell, he noticed that the fire had started near the engine/exhaust area. Tussock grass, exotic grass, and matagouri were the dominant vegetation burned, and grass fuels were 100% cured. Ambient temperature was 32ºC, RH was 18%, and wind speed was 2 km/h.

Table 2.9 Details of fire occurrences in Canterbury from 2003-2009.

Fire Date	Location/Fire Name	Time Fire Began, or was Reported (24 hr clock)	Fire Cause	Fire size (ha)	Temperature (°C)	Relative Humidity (%)	Wind Speed (km/hr)	Topography	Fuels Burned	Reference
14/12/2003	Telegraph Road, near Norwood	After 13:00	Tractor (without spark arrester fitted) - glowing carbon particle from exhaust system	15.1	27.8	15	34	Flat	Grassland (90% cured), exotic trees, and shelterbelt	King 2003
8/09/2004	Patterson Creek Railway Viaduct	Reported at 12:35	Metal Sparks - from a bridge beam grinding operation on railway	0.9	16.5	20	9	Steep (up to 32°)	Gorse and grazed tussock	Taylor 2004
21/09/2004	Normanby Road	Reported at 2:52	Train (9 fires) - brakes had been left on from Dunedin to Timaru, causing hot metal to land in grass	0.50-1	cool	~	light breeze	Flat	Tussock & grasses	Bang 2004 and DOC 2004
11/02/2005	Birdling's Flat Turnoff	Reported at 10:00	Power Lines - swan flew into power lines, fell to the ground and started fire	0.50-1	15.9	80	10	Flat	Grass	DOC 2005a
31/08/2005	Patterson Stream	Reported at 14:47	Train	6	17.2	~	35	Steep to flat	Tussock, grasses and gorse - moved into native vegetation	DOC 2005c
13/10/2005	Cass Bank #1	Reported at 14:30	Train	0.6	10.9	~	15	Steep/ undulating	Tussock & grasses	DOC 2005b
24/01/2006	Cass Bank/ Lake Sarah	Reported at 16:39	Train - hot metal fallen off carriage	0.06	24.1	46	12	Flat	Tussock & grasses	DOC 2006b
24/07/2006	Otarama Bank	8:30	Train (2 fires) - hot metal thrown from wheel bearing fault from a coal wagon	0.01	8	52	24	~	Cured grasses	Taylor 2006b
1/11/2006	Boyle Fire (Lewis Pass)	Afternoon	Metal Sparks (7 fires) - from trailer that had been towed for 14 km with a collapsed bearing and without a wheel	2	15.3	32	10	Flat/ undulating	Tussock, grasses (50%cured), matagouri	Taylor 2006a
3/11/2006	Aorangi Road Washdyke	~	Fireworks	0.5	22.0	~	~	Flat	Tussock & grasses	DOC 2006a

Table 2.9 Details of fire occurrences in Canterbury from 2003-2009, cont.

Fire Date	Location/Fire Name	Time Fire Began, or was Reported (24 hr clock)	Fire Cause	Fire size (ha)	Temperature (°C)	Relative Humidity (%)	Wind Speed (km/hr)	Topography	Fuels Burned	Reference
1/12/2006	Waddington (Sheffield)	Reported at 2:43	Train (6 fires) - hot metal dropped from a broken axel on train	0.50-1	18	~	strong NW	Flat	Tussock & grasses	Teeling 2006
31/01/2007	Bayleys Road	21:00	Power Lines/Sparks - had fallen onto dry grass, earthing caused sparks	23	20	44	2.7	Flat	Grasses	Campbell & Lane 2007a
25/02/2007	Spotswood	14:00	Train (4 fires) - hot molten metal was expulsed from train caused by a collapsed bearing	12	30	32	8.5	Flat	Grazed pasture & some tussock	Campbell & Lane 2007c
30/05/2007	Burneys Road	~	Lawn Mower - stick got jammed into mower and ignited dry grass	0.01	17.2	45	~	Flat	Grass & tussock	DOC 2007a
11/07/2007	Evans Pass	Reported at 20:37	Fireworks	0-0.01	19.4	55	10	Steep	Tussock & grasses	DOC 2007b
4/12/2007	Bridle Path Fire	Reported at 14:00	Metal Sparks or Hot Carbon - from exhaust of brush cutter	2	18.8	62	~	~	Tussock & light grasses	Campbell & Lane 2007b
16/01/2008	Corner Knob	Reported at 13:39	Metal Sparks - from railway line cutting operation using a petrol-powered cut off saw	52	30.1	20	3 to 6	Steep	Tussock, grasses (80% cured), manuka, matagouri, & hebe	Campbell 2008 and Taylor 2008
27/02/2008	Cass Bank	2:30	Train	0.01-0.5	~	~	~	~	Tussock & grasses	DOC 2008a
14/05/2008	Tikao Bay Road	Observed early morning and extinguished, reignited in afternoon	Fireworks	0.01	12	65	2	40° road side	Tussock, grasses, & scrub	DOC 2008e
11/10/2008	The Lakes Road	~	Vehicle	0-0.01	~	~	~	~	~	Teeling 2008b

Table 2.9 Details of fire occurrences in Canterbury from 2003-2009, cont.

Fire Date	Location/Fire Name	Time Fire Began, or was Reported (24 hr clock)	Fire Cause	Fire size (ha)	Temperature (°C)	Relative Humidity (%)	Wind Speed (km/hr)	Topography	Fuels Burned	Reference
29/10/2008	Quailburn	Detected after fire had self-extinguished	Vehicle - 4WD had become stuck off road	5 to 10	~	~	~	~	Tussock & grasses	Teeling 2008c
19/11/2008	Godley Head Roadside	~	Fireworks	0-0.01	23	31	~	Steep	Tussock & pasture (65%cured)	Teeling 2008a
25/01/2009	Hanmer	~	ATV - hay had accumulated around exhaust system	15	31.5	11	13	~	Grasses (90 - 100% cured)	Barnes, personal communication, December 16, 2009
28/02/2009	Lake Road South	~	Vehicle - light truck had been doing donuts, which caused fire	0-0.01	17.8	67	~	Flat	Pasture (85% cured)	Teeling 2009a
10/03/2009	McConnels Road	~	Power Lines - fallen	0.01-0.5	21.5	36	~	Flat	Pasture (80% cured)	Teeling 2009b

2.6 Summary

Findings from this literature review support those of Babrauskas (2003), namely that many studies are difficult to compare with one another, and that experimental methods can be distinct from one another. Furthermore, experimental conditions vary between studies. Some commonalities can be synthesised from the literature, but further work is required to clearly define ignition thresholds for grassland fuels.

ATVs, trains, lawnmowers, and machinery pose significant hot metal ignition risk to grass fuels. Other vehicles, such as utility trucks, can also cause ignitions, especially if they are working under strenuous conditions. Cured grass fuels, with less than 15% MC, can ignite at metal temperatures as low as 310ºC if wind is present, and sample length is quite short (Pitts, 2007). Without wind, grass longer than 2.5 cm can ignite at 440ºC (Pitts, 2007).

While reports suggest that exhaust gas, hot carbon, and metal sparks can ignite grass fuels, little work has been completed in this area. More studies are needed, under a range of conditions, to understand the ignitibility of grass fuels from carbon emissions and metal sparks.

Many studies have investigated the ignitibility of grassland fuels from organic embers, cigarettes, firebrands, and other similar sources. ATVs can ignite material accumulated on hot exhaust parts, posing a risk to surrounding ground fuels. Firebrands are also a high ignition risk, yet usually fall from burning fires, causing spot fires away from the main fire. Managers conducting prescribed burns need to be aware of flaming and smouldering firebrands. The probability of ignition from cigarettes or cigars is very low compared with the other ignition sources reviewed.

Open flame sources pose a high ignition risk, possibly igniting dead grass containing up to about 40% MC (Blackmarr, 1972; de Groot *et al.*, 2005; Dimitrakopoulos *et al.*, 2010).

Table 2.10 presents a summary of work reviewed in this chapter that focused specifically on the ignition of grass fuels under various conditions. In most cases, the hot metal temperature threshold that ignited grass fuel was between 310 and 400ºC for samples containing less than 14% MC. Wind presence tended to lower the hot metal temperature required for ignition. The studies using hot gases as ignition sources reported temperatures between 370 and 440ºC; but Di Blasi *et al.* (1999) reported a very low temperature (276ºC), and Fairbank and Bainer (as cited by Babrauskas, 2003) reported a very high temperature (663ºC). These findings do not compare with other reported thresholds. Grass ignition from cigarettes and cigars is possible under certain environmental conditions, when MC is less than 14% (Sale & Hoffheins, 1928;

Countryman, 1983). Studies suggested that the ignition thresholds of dead grass fuels from open flame are of MC values between 38 and 44%, whereas live grass fuels with higher MC values were found to burn more readily than dead fuels (de Groot *et al.*, 2005; Dimitrakopoulos *et al.*, 2010). Embers have been found to ignite grass fuels with up to 11% MC. This contrasts with Cheney and Sullivan (2008), who report that grass fuels cannot ignite from embers unless they contain less than about 6% MC. Firebrands have been found to ignited dead grass at MC levels up to 43% (Guijarro *et al.*, 2002). Furthermore, studies found that as grass fuel density increases, so does the likelihood of successful ignition (Sale & Hoffheins, 1928; Guijarro *et al.*, 2002). The behaviour of grass fuels from exposure to different ignition sources is still largely unknown, but this review has provided an indication of various experiments and ignition sources that have been previously investigated.

Table 2.10 Summary of conditions conducive to ignition of grass fuels from different ignition sources, where thresholds are reported for the given MC values and wind speeds, and notes refer to experimental parameters (inapplicable or unknown denoted as ~).

Ignition Source	Grass Type or Species	Ignition Type (GI/FI)*	Ignition Threshold Temperature (°C)	MC (%)	Wind Speed (m/s)	Notes	Probability of Ignition/ Threshold	Reference
Hot Metal	dry grass	FI	663	?	0	~	~	Fairbank & Bainer as cited by Babrauskas 2003
Hot Metal	dry grass	FI	400	dry	0.9	4 min exposure time	~	Harrison as cited by Babrauskas 2003
Hot Metal	fine veld	FI	400	dry	blowing on sample	~	~	Rallis and Mangaya 2003
Hot Metal	tall fescue (live)	FI	310	10 to 14	2.5	~	~	Pitts 2007
Hot Metal	tall fescue (live)	FI	340	10 to 14	0	~	~	Pitts 2007
Hot Metal	tall fescue (dead)	FI	310	10 to 14	1.0	~	~	Pitts 2007
Hot Metal	tall fescue (dead)	FI	371	10 to 14	0	~	~	Pitts 2007
Hot Metal	cheat	FI	350	10 to 14	2.5	~	~	Pitts 2007
Hot Metal	cheat	FI	380	10 to 14	0	~	~	Pitts 2007
Hot Metal	fine Florida (unidentified mix)	FI	310	10 to 14	1.0	~	~	Pitts 2007
Hot Metal	fine Florida (unidentified mix)	FI	320	10 to 14	0	~	~	Pitts 2007
Hot Metal	dry grass	FI	525	0	1 to 1.5	vertical orientation	~	Knight & Hutchings 1987
Hot Metal	dry grass	FI	400	0	1 to 1.5	cradled orientation	~	Knight & Hutchings 1987
Hot Metal	cheat	FI	270	6	0	piloted	~	Kaminski 1974
Hot Metal	fine veld	GI	250 to 350	?	0	~	~	Rallis and Mangaya 2003

* GI -Glowing Ignition, FI - Flaming Ignition

Table 2.10 Summary of conditions conducive to ignition of grass fuels from different ignition sources, where thresholds are reported for the given MC values and wind speeds, and notes refer to experimental parameters (inapplicable or unknown denoted as ~), cont.

Ignition Source	**Grass Type or Species**	**Ignition Type (GI/FI)***	**Ignition Threshold Temperature (ºC)**	**MC (%)**	**Wind Speed (m/s)**	**Notes**	**Probability of Ignition/ Threshold**	**Reference**
Hot Metal	cheat	GI	330	6	0	10 min exposure, but ambient temp 35.6ºC	~	Kaminski 1974
Cigarettes	dry grass	~	~	< 12	2.8	0.043 g/cm^3 density	50%	Sale and Hoffheins 1928
Cigarettes	dry grass	~	~	< 12	2.8	0.099 g/cm^3 density	80%	Sale and Hoffheins 1928
Cigarettes	cheat (dead)	FI	~	≤ 14	1.3	≤ 3.85 cm long		Countryman 1983
Cigars	dry grass	~	~	< 12	2.8	0.043 g/cm^3 density	25%	Sale and Hoffheins 1928
Cigars	dry grass	~	~	< 12	2.8	0.099 g/cm^3 density	40%	Sale and Hoffheins 1928
Open Flame (drip torch)	slender oat (live and dead)	~	~	38.5	0 to 11.1	~	50%	Dimitrakopoulos *et al.* 2010
Open Flame (flaming matches)	kunai (dead)	FI	~	< 60	0	~	35% MC	de Groot *et al.* 2005
Open Flame (flaming matches)	kunai (live)	FI	~	< 70	0	~	28% MC	de Groot *et al.* 2005
Non-flaming Firebrands	dry cow dung	FI	~	< 11	2.68	< 2.0 X 0.5 cm size	~	Bunting & Wright, 1974
Flaming Embers	dry cut grass	FI	~	11	0.5 or 1.0	Ignited from 4 flaming embers (50 mm diameter, 6 mm thick)	~	Manzello *et al.* 2006
Flaming Firebrands	dry grass (dead)	FI	~	< 50	0	vertical orientation	43% MC	Guijarro *et al.* 2002
Flaming and Glowing Firebrands	various grass species (live and dead)	FI	~	< 75	1 or 2.9	vertical and horizontal orientation	~	Curt *et al.* 2007
Convective Heating	dry straw	FI	276	7	1.9	~	~	Di Blasi *et al.* 1999
Convective Heating	dry straw	FI	376	7	0.35	~	~	Di Blasi *et al.* 1999
Furnace	cheat (dead)	FI	440	≤ 18	0	~	~	Stockstad 1976
Furnace	cheat (dead)	FI	370	≤ 18	0	piloted	~	Stockstad 1976

* GI -Glowing Ignition, FI - Flaming Ignition

This chapter also included a review of several Canterbury grass fires that have occurred from human ignition sources. Many of these fires could have been prevented if vehicles and equipment were functioning properly, or if the ignition thresholds of grassland fuels were understood. More research is needed to accurately define ignition thresholds from the various ignition sources that have been found to ignite grassland fuels.

Chapter 3. Methods

3.1 Introduction

Experiments were divided into two parts. First, laboratory experiments were conducted under controlled conditions. Second, a set of field-based experiments were conducted and findings were compared against those from the laboratory. Experiments aimed to determine the ignition thresholds of tussock and exotic grasses by varying ignition source, moisture content (MC) and wind speed. The results were used to model probability of ignition success from the different ignition sources, using logistic regression (Chapter Four).

Laboratory experiments were divided into five categories based on ignition sources of highest concern to DOC fire managers. They were hot metal contact, hot carbon emissions, organic embers, metal sparks, and open flame. These categories were chosen to simulate the ignition sources reviewed in Chapter Two. The methodologies of ignition testing for each experimental category, as well as the scenario the experiment was meant to represent, are explained in detail in section 3.4. Tussock and exotic grass samples were tested for ignitibility within each category and were conditioned to several different MC classes to ensure the data-set included an adequate number of observations for analysis. Each experiment included between 12 and 91 trials, depending on the ignition category, and each trial was repeated three times to increase credibility of the results. The following sections explain grass-sample preparation, experiment design, and the methodologies of ignition testing for each category.

The field-based experiments tested both grass-types in all categories except organic embers. The methodologies employed are detailed in section 3.5.

3.2 Grass Samples and Moisture Content

3.2.1 Sample Collection and Preparation

As described in Chapter One, many types of grass species are found throughout grasslands. Tussock grasses grow in clumps and are usually interspersed with exotic grasses. Arrangement of grass in the field can affect fire spread, but this research only investigated ignition probability, not fire spread mechanisms. Once ignition occurs, existing fire behaviour models can be applied to determine fire spread and extent (Pearce & Anderson, 2008). Samples contained 100% cured grasses, because fuel in that state poses the highest ignition risk, especially at low MC levels (Cheney & Sullivan, 2008). The experiments did not consider other curing levels due to time constraints. Alexander (2008) related degree of curing with the Initial Spread Index component of the FWI System (Figure 1.9, Chapter One), which is used to determine grassland fire danger classes. It showed that fire danger is highest when the degree of curing is 100%.

Throughout autumn and winter (April to September), grass samples were collected from Hakatere Conservation Park (within the Ō Tū Wharekai wetland restoration area). The locations were slightly south of Lake Clearwater (E1442550º, N5169750º), and just north of Lake Emma (E1446655º,N5167893º) as shown in Figure 3.1. Grass species at these locations were abundant with similar distributions. Figure 3.2 shows the collection site locations in relation to Christchurch. When collected, most grasses were at the end of their life cycle in a dead, or cured state (Figure 3.3). Tussock grass samples consisted of hard tussock (*Festuca novae-zelandiae*), whereas exotic grass samples included a combination of brown top (*Agrostis capillaris*) and small amounts of sweet vernal (*Anthoxanthum odoratum*). These two grass types were elected for testing due to their prevalence and their different structural characteristics. Some tussocks were not fully cured, so they were dug from the ground with roots attached and left in the laboratory to die and fully cure. Care was taken to cut only fully cured exotic grass. This was achieved by cutting approximately 10 cm above the shorter, uncured grass blades/tillers. Exotic grass was placed into paper bags, ensuring each blade was facing the same direction for sample consistency (Figure 3.3).

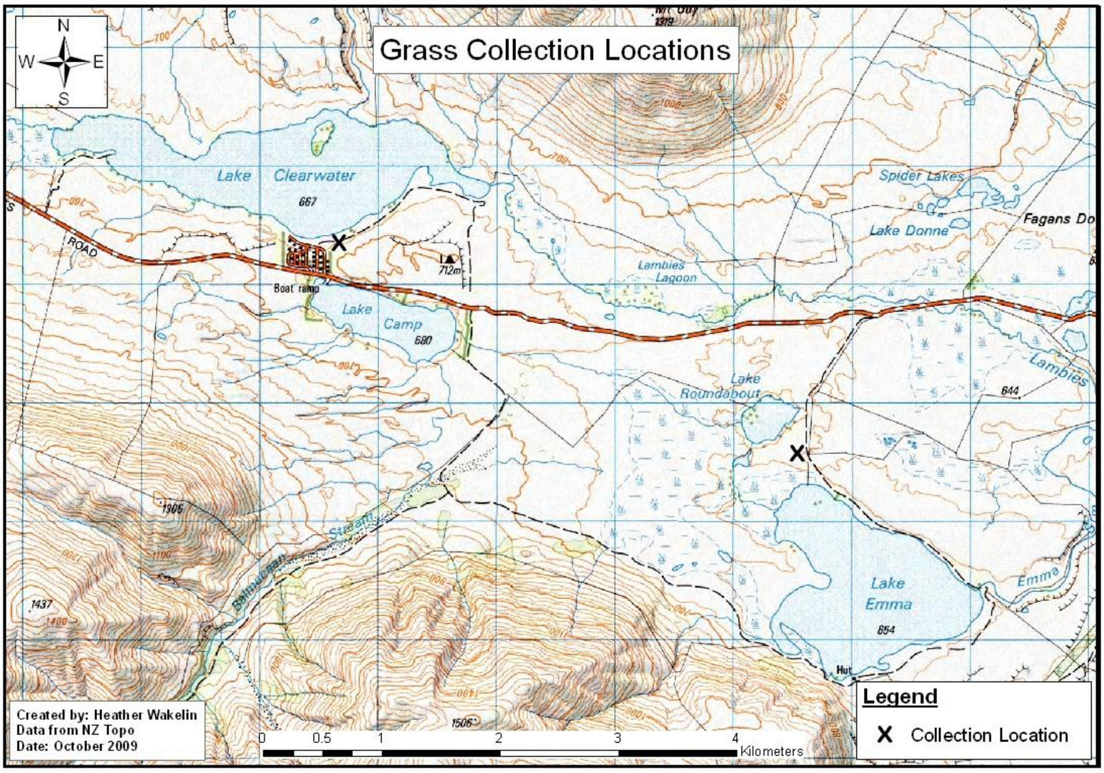

Figure 3.1 Grass collection locations.

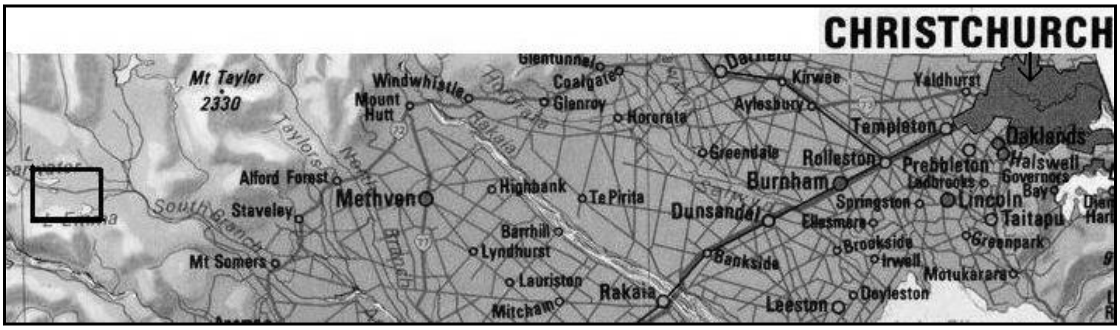

Figure 3.2 The approximate location of grass collection sites in relation to Christchurch, scale approximately 1:1 million (data from Integrated Mapping, 2009).

Figure 3.3 From left to right: a cured tussock in the field, collection of cured exotic grass next to Lake Clearwater, and cured exotic grass in collection bag.

The collection locations were at elevations of approximately 650 to 700 m above sea level. Surrounding areas consisted of flat valley bottoms and steep hills of varying heights up to 2900 m. Typical fuel loads for the two grass types were determined using fuel load models derived by Fogarty and Pearce (2000). For areas that included tussock and exotic grasses, cover was about 80%. Average tussock height was about 50 cm, resulting in a fuel load estimation of about 16.0 t/ha of total above-ground biomass (TAGB). For areas that contained ungrazed exotic grass and no tussock, the cover was about 70%. The average exotic grass height was about 30 cm, resulting in a fuel load estimation of about 4.8 t/ha of TAGB. The grassland areas contained highly variable amounts of grasses, and the fuel load estimations are approximate.

In the laboratory, all grass samples were arranged to represent their natural orientation. Other orientations were considered, such as litter beds, but were discarded due to time constraints. Samples were held in aluminium cans of 5.0 cm diameter and 11.2 cm height (220 cm^3), which had 1.2 x 1.2 cm wire mesh fitted over their open tops (Figure 3.4). Grass was cut to lengths of not more than 25 cm before placing through the mesh and into the cans in a vertical orientation (Figure 3.5). Care was taken to ensure all samples were as uniform as possible. The average oven-dry weight was 11.4 g ± 0.1 s.e. (standard error), and 5.5 g ± 0.1 s.e. for tussock and exotic grass samples respectively. The tussock samples were representative of the density of an average tussock grass in the field. Exotic samples were designed to represent highly dense areas of exotic grass in the field, which ensured enough fuel in the sample can to support ignition.

Figure 3.4 View of empty sample cans with mesh tops.

Figure 3.5 Example of exotic (left) and tussock (right) samples used for laboratory experiments.

3.2.2 Moisture Content Classes

As reviewed in Chapter Two, Cheney and Sullivan (2008) state that ignition of dead grass fuels is predominantly influenced by MC and only prolonged flames can trigger ignition at

MC levels above 15 to 20%. Moreover, ignition from hot particles, sparks, and embers becomes progressively easier below 6% MC. Based on these statements, several MC classes were proposed to determine the effect of different ignition sources on ignition behaviour of grasses containing various MC levels (Table 3.1). These classes were based on the assumption that ignition would not occur over 20% MC for all ignition sources but open flame.

Table 3.1 MC classes.

MC Class (%)
0.00 to 2.99
3.00 to 5.99
6.00 to 10.99
11.00 to 15.99
16.00 to 22.99
23.00 and above

The MC classes provided a guide to ensure that different MC values were tested, especially in the low range. As experiments progressed, additional classes between 23.00 and 175.00% MC were tested, because ignition occurred at higher MC values than were anticipated (detail in section 3.4). Pilot tests determined that two different procedures were needed to achieve the desired MC values: namely ‘moisture absorption/adsorption,’ and ‘moisture evaporation.’ Regardless of the procedure, each test sample was accompanied by an associated sample, which was conditioned to the same MC level. The associated sample was never burned, and was used to calculate MC, which corresponded to the burned sample.

The ‘moisture absorption/adsorption’ method was used to achieve MC values below about 11%. Samples and associated samples were oven-dried at 105ºC for 48 hours to ensure all moisture was removed. As soon as samples were removed from the oven, their weights were recorded. Samples were then left in ambient air in the laboratory for varied lengths of time to absorb/adsorb moisture from the air and achieve the desired MC class (Table 3.2). Immediately before tests commenced, samples were reweighed. MC was calculated using gravimetric analysis, where dry mass was compared with wet mass, using Equation 3.1.

Equation 3.1 $$MC = ((\text{wet mass} - \text{dry mass})/\text{dry mass}) \times 100$$

Table 3.2 Approximate time samples were left in the laboratory to absorb/adsorb moisture and reach the appropriate MC class.

Grass Type	MC Class (%)	Time left at room temperature (min)
Tussock	6.00 to 10.99	1000
Tussock	3.00 to 5.99	120
Tussock	0.00 to 2.99	2
Exotic	6.00 to 10.99	480
Exotic	3.00 to 5.99	60
Exotic	0.00 to 2.99	1

The 'moisture evaporation' method was used to achieve MC values of about 11% and higher. Before putting the grass into cans, it was submerged in water for approximately two minutes. Next, the grass was removed, excess water was squeezed out, and the grass was dabbed with newspaper. It was put into the oven at 40ºC for varied lengths of time to reach the desired MC. Once removed from the oven, the grass was put into cans, and associated samples were weighed immediately before tests commenced. The MC of the associated sample was assumed to represent that of the test sample. This was because the test samples were either destroyed and/or the MC was altered during the experiments; therefore, test samples could not be oven-dried to determine the dry mass. Once weighed, associated samples were oven-dried at 105ºC for 48 hours to ensure all moisture was removed. They were then reweighed and MC was calculated using Equation 3.1.

The 'moisture evaporation' method was based on trial-and-error. For example, if all samples flamed in trial repetitions, then a higher MC level was needed to find the ignition threshold; in this case, the next samples were taken out of the oven sooner so they would have a higher MC. If none of the samples ignited, then the next samples were left in the oven longer to condition them to a lower MC. Oven drying times ranged from approximately 20 to 180 minutes. Many extra trials were completed for ignition sources that caused flaming ignition of samples with high MC levels. It was also noted that the MC variability between samples increased as MC increased. This would also be expected amongst fuels in the field, due to sheltering and variable exposure of fuel elements to moisture and drying. MC classes for samples with high MC levels were therefore much wider than for samples with low MC levels.

3.3 Laboratory Experiments

Laboratory experiments were designed to simulate and test five potentially dangerous ignition sources. The main null hypothesis was that there is no difference in the behaviour of cured tussock and exotic grasses (regardless of MC) when exposed to the five ignition sources at various wind speeds. For those experiments where flaming ignition was not immediate, the secondary null hypothesis was that there is no correlation between grass MC, time-to-ignition, and wind speed.

Grass samples were tested for ignitibility from the five ignition sources reviewed in the following section (3.4). For each ignition source, several trials were conducted. Each trial consisted of three repetitions of samples conditioned to the same MC class. Each repetition was classified into one of three categories: ‘flaming ignition’ (FI) was recorded if flames were present, and the sample burned completely down to the top of the sample can within 30 seconds of ignition source removal; ‘glowing ignition’ (GI) was recorded if sample fuel was glowing when the repetition ended but not flaming, and the glowing fuel area was larger than 5 mm in diameter; and, ‘no ignition’ (NI) was recorded if the sample did not ignite, or did not burn completely within 30 seconds of ignition source removal. If samples flamed or glowed, ‘time-to-ignition’ was recorded, which was the time from initial contact between the ignition source and the sample to the time when ignition occurred. Sometimes, glowing fuel was initially difficult to see, which may have caused the time-to-ignition to be over-estimated in these cases. Each trial was repeated for both grass types, where most experiments were video recorded, and comments were noted for each repetition when appropriate. The experiments were designed with the following assumptions:

- the arrangement of grass in the samples was consistent;
- if an ignition source was present (in the laboratory or the field), it would come into contact with grassland fuels;
- the experiments were testing for the worst-case scenarios that would exist in the field, where worst-case refers to fully-cured grass, low MC levels, relative humidity (RH) < 50%, and ambient temperature > 18ºC; and
- ambient temperature and RH were relatively constant in the laboratory.

A list of the main experimental variables is provided in Table 3.3. Wind speed was varied to 0, 1, and 2 m/s for all experiments except hot carbon emissions. These speeds fit into the Beaufort scale wind classes one and two, which are referred to as very light and light wind speeds respectively (Chandler *et al.*, 1983). Class one includes 0 – 1.5 m/s, and class two includes 1.5 – 3.0 m/s. Hot carbon experiments had a constant 200ºC air flow of 3.7 m/s, which was required to simulate hot exhaust gases and sparks leaving a vehicle tailpipe. The experiments included all variables listed, with some experiments having additional variables. These are fully explained in section 3.4.

Table 3.3 Experimental variables.

Grass Type	Igniton Source	Wind Speed or Air Flow* Reported Values (m/s)	Wind Speed or Air Flow* Actual Values (m/s ± s.e.)	Temperature (°C ± s.e.)	Relative Humidity (% ± s.e.)	MC Classes (%)
Tussock	Hot Metal	0	0.061 ± 0.001	21.8 ± 0.1	34.7 ± 0.2	0.00 to 2.99
Exotic	Carbon Emissions	1	1.01 ± 0.02			3.00 to 5.99
	Metal Sparks	2	2.00 ± 0.05			6.00 to 10.99
	Organic Embers	3.69*	3.69 ± 0.01*			11.00 to 15.99
	Open Flame					16.00 to 22.99
						23.00 and above

Wind speed was measured by a Dantec, hot-wire sonic precision anemometer, Type 54N60. For all experiments except hot carbon emissions, an ordinary three-speed household fan (Antarctica 40 cm Stand Fan) was used to vary wind speed (Figure 3.6). This was similar to the fans used by Curt *et al.* (2007), Pitts (2007), and Plucinski and Anderson (2008). Wind direction was always perpendicular to the ignition source. Each time wind speed was changed, the sonic anemometer was used for calibration. Table 3.3 shows the reported wind speed values, which represent mean wind speed and standard error for all laboratory experiments except hot carbon.

Figure 3.6 Antarctica 40 cm Stand Fan (3 speeds).

Ambient temperature and RH were measured by a TempTec™ hygrometer/thermometer and recorded for the repetitions of all trials (Table 3.3).

3.4 Ignition Sources

3.4.1 Hot Metal Contact

A heated copper plate was used to simulate hot metal ignition sources from vehicle exhaust systems, such as off-road utility vehicles or ATVs, or from other hot equipment, such as industrial lawn mowers or brush cutters. The ‘hot metal experiment’ procedure was designed to simulate an idling vehicle which had stopped for five minutes. Samples were clamped into place using a retort stand and the hot plate was fixed in two different orientations (horizontal and vertical). Timing began when contact was made with the grass sample. Due to time constraints, samples were left in contact for a maximum of five minutes. If fuel burned before five minutes had elapsed, the trial was completed and the time-to-ignition was recorded. The remainder of this section explains the rationale for and details of the hot metal experimental procedure.

The hottest part of an exhaust system is at the manifold (500 – 550ºC), and temperatures slowly decrease as the exhaust gas reaches the tailpipe (Heisler, 1999; Cole, 2001; DeHaan, 2002). Table 2.1 (Chapter Two) shows reported temperatures of hot exhaust systems at different locations on several vehicles. Prior to designing the hot metal experiment, a field test was conducted to compare exhaust system temperatures with published reports. On September 10, 2009, a utility vehicle (an unloaded 2006 Nissan Navara, 4WD turbo diesel, with manual transmission) was driven on gravel roads and off-road tracks in Hakatere Conservation Park. On September 11, 2009, the test was repeated on off-road tracks in the Christchurch Port Hills in order to verify findings. The gravel roads were mostly flat, except for one 7% slope over 1 km, while the off-road tracks featured rolling hills. The weather was clear, windy and cool (~ 13ºC). Type-K thermocouples (24-gauge) were attached to the exhaust system in eight places from the manifold (turbo inlet) to the tailpipe. A data-logger recorded the thermocouple temperature every second. Temperatures reached 393ºC, but tended to remain below 300ºC when driving slower than 60 km/h (Figure 3.8). When the Nissan was in idle, all temperatures at the thermocouple locations dropped. Figure 3.7 shows selected thermocouple locations and their corresponding channels (refer to Figure 3.8). These measurements are in the same range as values reported in the literature (Heisler, 1999; Cole, 2001; DeHaan, 2002; Babrauskas, 2003; Bosch, 2004; Gonzales, 2008); however, the exhaust system has the potential to reach higher temperatures if fully loaded, with the engine working harder (Knight & Hutchings, 1987). Temperature measurements of an ATV would have been useful, but were not completed due to time and resource constraints.

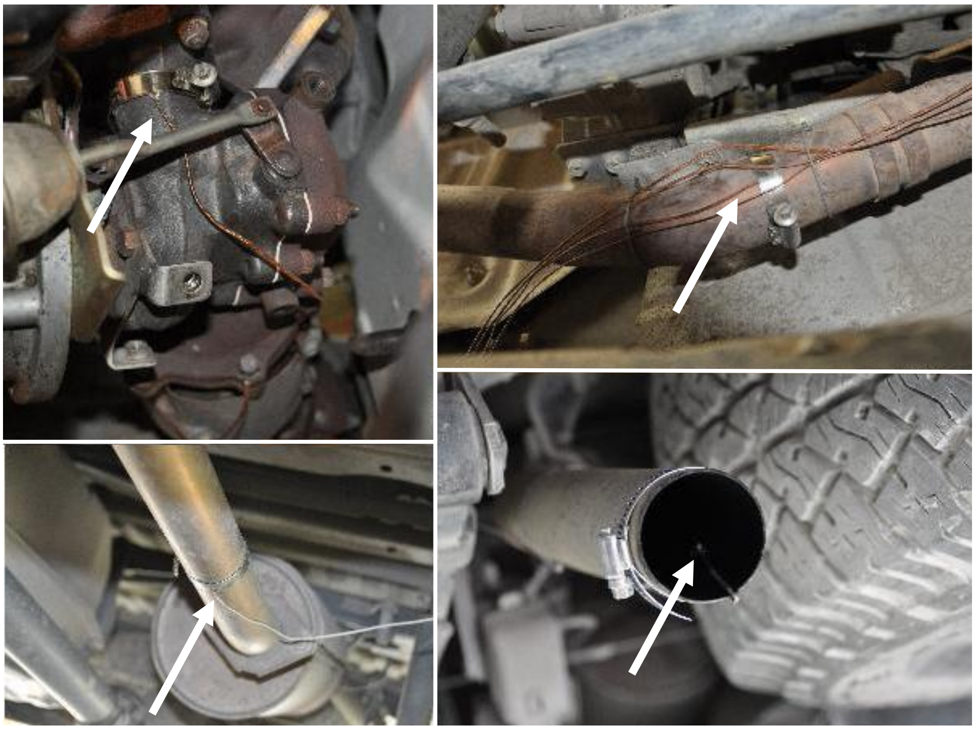

Figure 3.7 Thermocouple locations on the 2006 Nissan Navara, clockwise from top left: turbo inlet (Channel 1), exhaust at transfer case (Channel 4), exhaust gas (Channel 8), and second muffler outlet (Channel 7).

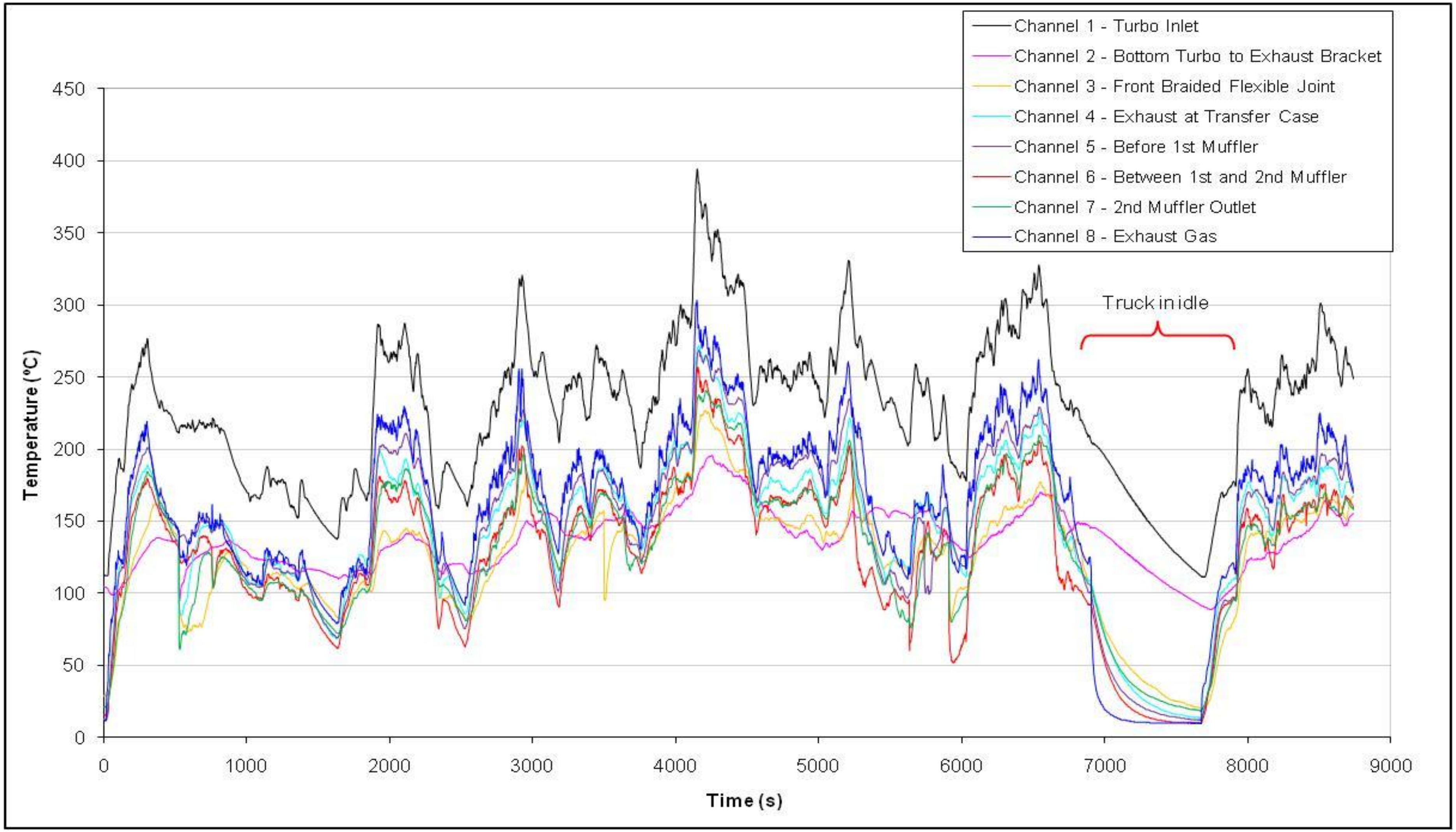

Figure 3.8 Temperatures of selected locations of the exhaust system of the 2006 Nissan Navara.

In the laboratory, hot plate temperatures were chosen to represent temperatures of actual exhaust systems. Under normal driving conditions, exhaust system parts below the manifold of utility 4WD vehicles rarely reach temperatures as high as 500°C (Heisler, 1999; Cole, 2001; Gonzales, 2008), but ATV exhaust system temperatures have been recorded as high as 585ºC at the manifold (Baxter, 2004). This distinction is important, as the likelihood of grass fuels making contact with an ATV manifold is much higher than with a utility 4WD vehicle manifold. ATV manifolds are closer to the ground and easier for long grass to make contact with compared to utility 4WD manifolds. Furthermore, minimum temperatures between 300 and 500ºC have been reported to ignite grass fuels (Table 2.10, Chapter Two). These values indicated the temperature range required by the hot plate.

Pilot testing involved a 1.2 mm diameter, grade 316, stainless steel hot plate set to various temperatures up to 500ºC, and investigated temperature variability at different locations on the hot plate surface. A Raytek Raynger® MX™ infrared thermometer was used to measure average surface temperatures, which determined that the stainless steel hot plate temperature was inconsistent, varying by over 20°C from one area to another. Consequently, a heated copper plate was constructed using materials and specifications similar to those used for the heated plate fabricated by Pitts (2007). Copper has high heat-conducting properties, making it an excellent medium for building a hot plate requiring uniform temperatures. Hot plate dimensions were 14.4 x 9.9 cm, and thickness was 2.0 cm. Three 1.0 cm diameter holes were drilled into the long side and spaced at 2.3, 5.0, and 7.7 cm from the plate edge. Cylindrical Superwatt® High Watt Density heaters, rated to 220 watts, were inserted into the holes and connected to a temperature control system and power supply. They were 10.0 cm long, and 1.0 cm in diameter. The copper plate was fitted onto a metal support which allowed it to be moved up and down.

The hot plate tested ignitibility in two orientations: horizontal and vertical. Samples were clamped into place for testing, using a retort stand. The horizontal orientation simulated contact between the tops of grass fuels, and ground-facing hot vehicle parts (Figure 3.9). A hose clip was positioned on the hot-plate metal support, which stopped the hot plate at 4.2 cm above the sample for each trial. When each trial began in the horizontal orientation, the hot plate was moved down on top of the grass until it was stopped by the hose clip. This caused the tops of the grass samples to be pushed down, increasing contact with the hot plate. The vertical orientation simulated contact between the side of grass fuels and side-facing hot vehicle parts (Figure 3.10). When each trial began in the vertical orientation, the grass sample was moved into the hot plate at a slight angle, which ensured they were in full contact. The photographs and schematic diagrams indicate that wind direction was perpendicular to the grass samples in both experimental designs (Figures 3.9, 3.10, 3.11, and 3.12).

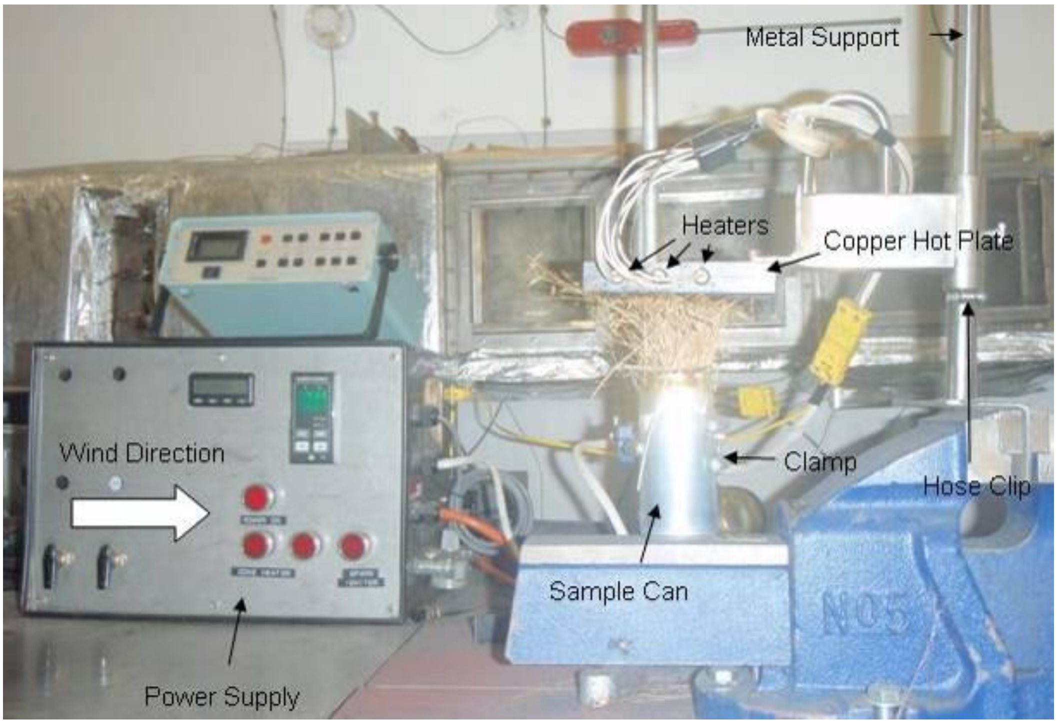

Figure 3.9 Hot metal experimental set-up: horizontal hot plate orientation.

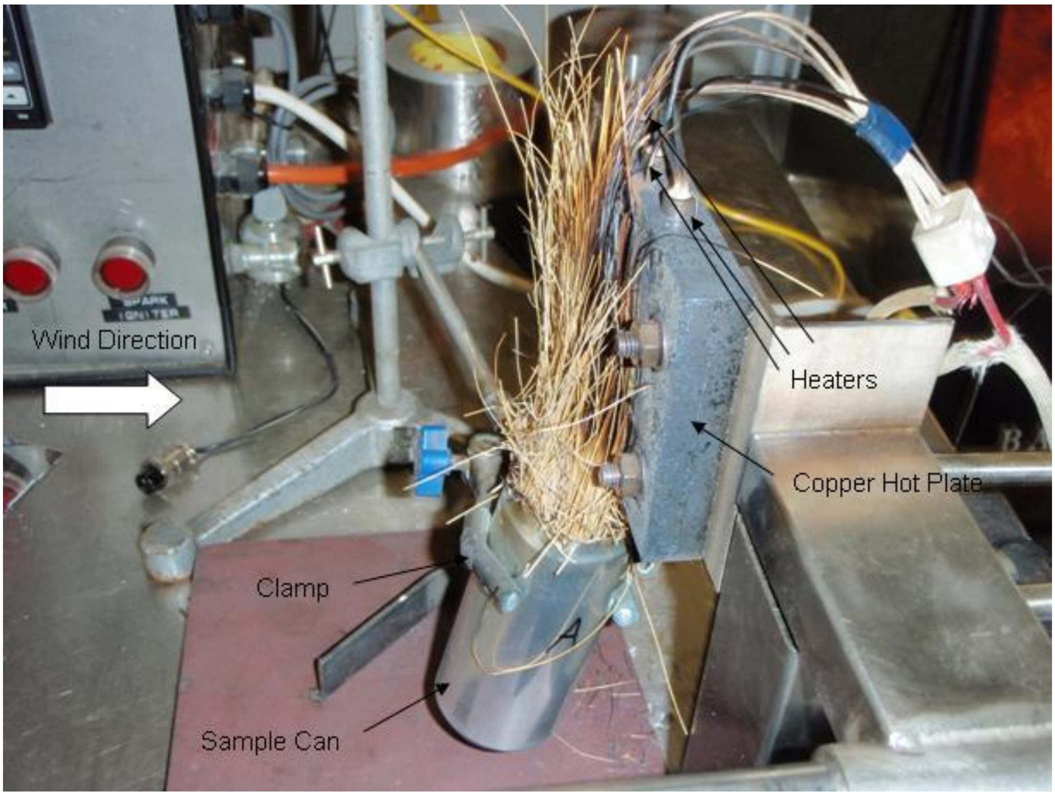

Figure 3.10 Hot metal experimental set-up: vertical hot plate orientation.

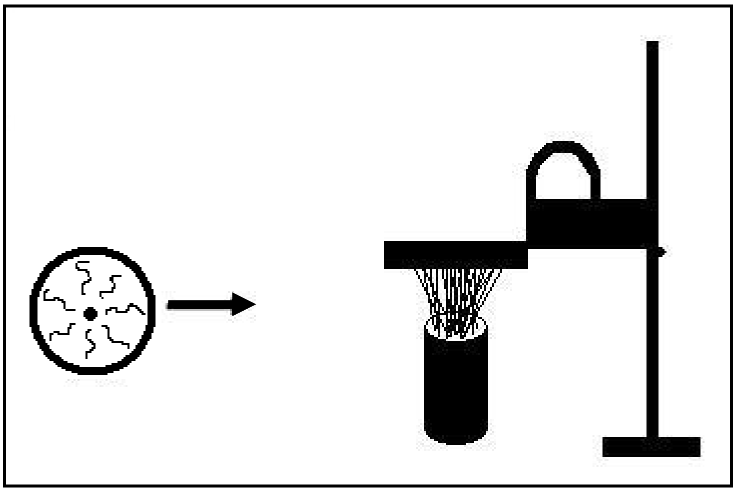

Figure 3.11 Schematic of the horizontal hot metal experimental set-up, with an arrow indicating wind direction (not to scale).

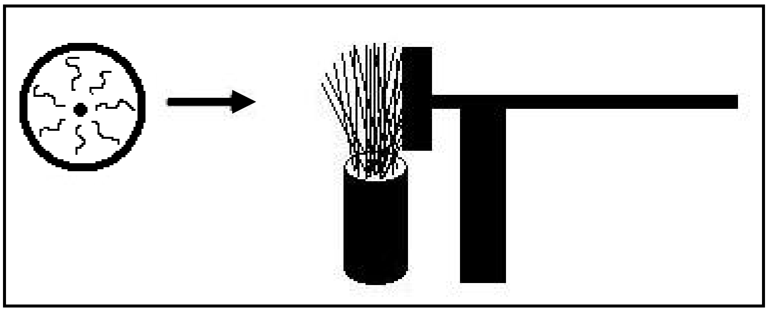

Figure 3.12 Schematic of the vertical hot metal experimental set-up, with an arrow indicating wind direction (not to scale).

Actual hot plate temperatures ranged from 366 to 493°C. There were no ignitions at the lowest temperature, so experiments continued at progressively higher temperatures. When wind was applied to the sample and hot plate, the hot plate's temperature decreased; this explains why the reported hot plate temperatures are not rounded numbers. For each set hot plate temperature, and each of the three wind speeds, a 0.254 cm-gauge type-K thermocouple was used to measure the temperature of five locations on the hot plate: the centre, and each of the four corners. This was repeated four times at each location, for a total of 20 times per set temperature and wind speed. This value was averaged and reported for each trial (Table 3.4). The standard error was below ± 1ºC for seven of the set temperatures, and below ± 2.4ºC for the other eight set temperatures.

Three trials were completed for every combination of grass type, temperature, and MC class, where in most cases, each combination was repeated three times at each of the three wind speeds. Table 3.4 reports the specifications for each trial. In the 'Grass Type' column, Tussock/Exotic refers to trials that were completed with the same specifications for each grass type. Trials 1 to 9 began with the lowest MC class (0.00 to 2.99), with subsequent trials containing different MC classes depending on the previous results. Very few ignitions occurred in the horizontal orientation, which explains the lack of MC class variability for this orientation. More trials, at higher MC classes, were completed for the vertical orientation because FI was observed at higher temperatures. There were 55 trials for tussock grass, and 36 for exotic grass.

Table 3.4 Trial specifications for hot metal experiments.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)	Average Hot Plate Temperature (ºC)	Orientation
Tussock/Exotic*	1	0	0.00 to 2.99	481	Horizontal
Tussock/Exotic	2	1	0.00 to 2.99	445	Horizontal
Tussock/Exotic	3	2	0.00 to 2.99	384	Horizontal
Tussock/Exotic	4	0	0.00 to 2.99	453	Horizontal
Tussock/Exotic	5	1	0.00 to 2.99	424	Horizontal
Tussock/Exotic	6	2	0.00 to 2.99	366	Horizontal
Tussock/Exotic	7	0	0.00 to 2.99	431	Horizontal
Tussock/Exotic	8	1	0.00 to 2.99	418	Horizontal
Tussock/Exotic	9	2	0.00 to 2.99	393	Horizontal
Tussock/Exotic	10	0	3.00 to 5.99	407	Horizontal
Tussock/Exotic	11	1	3.00 to 5.99	402	Horizontal
Tussock/Exotic	12	2	3.00 to 5.99	380	Horizontal
Tussock/Exotic	13	0	0.00 to 2.99	382	Horizontal
Tussock/Exotic	14	1	0.00 to 2.99	379	Horizontal
Tussock/Exotic	15	2	0.00 to 2.99	370	Horizontal
Tussock/Exotic	16	0	0.00 to 2.99	381	Vertical
Tussock/Exotic	17	1	0.00 to 2.99	381	Vertical
Tussock/Exotic	18	2	0.00 to 2.99	380	Vertical
Tussock/Exotic	19	0	0.00 to 2.99	493	Vertical
Tussock/Exotic	20	1	0.00 to 2.99	431	Vertical
Tussock/Exotic	21	2	0.00 to 2.99	390	Vertical
Tussock	22	0	0.00 to 2.99	434	Vertical
Tussock	23	1	0.00 to 2.99	426	Vertical
Tussock	24	2	0.00 to 2.99	395	Vertical
Exotic	22	0	3.00 to 5.99	493	Vertical
Exotic	23	1	3.00 to 5.99	431	Vertical
Exotic	24	2	3.00 to 5.99	390	Vertical
Tussock	25	0	3.00 to 5.99	493	Vertical
Tussock	26	1	3.00 to 5.99	431	Vertical
Tussock	27	2	3.00 to 5.99	390	Vertical
Exotic	25	0	0.00 to 2.99	481	Horizontal
Exotic	26	1	0.00 to 2.99	445	Horizontal
Exotic	27	2	0.00 to 2.99	384	Horizontal
Tussock	28	0	0.00 to 2.99	481	Horizontal
Tussock	29	1	0.00 to 2.99	445	Horizontal
Tussock	30	2	0.00 to 2.99	384	Horizontal
Exotic	28	0	6.00 to 10.99	493	Vertical
Exotic	29	1	6.00 to 10.99	431	Vertical

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

Table 3.4 Trial specifications for hot metal experiments, cont.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)	Average Hot Plate Temperature (ºC)	Orientation
Exotic	30	2	6.00 to 10.99	390	Vertical
Tussock	31	0	3.00 to 5.99	434	Vertical
Tussock	32	1	3.00 to 5.99	426	Vertical
Tussock	33	2	3.00 to 5.99	395	Vertical
Exotic	31	0	60.00 to 89.99	493	Vertical
Exotic	32	1	90.00 to 119.99	431	Vertical
Exotic	33	2	90.00 to 119.99	390	Vertical
Tussock	34	0	6.00 to 10.99	493	Vertical
Tussock	35	1	6.00 to 10.99	431	Vertical
Tussock	36	2	6.00 to 10.99	390	Vertical
Exotic	34	0	90.00 to 119.99	493	Vertical
Exotic	35	1	120.00 to 149.99	431	Vertical
Exotic	36	2	90 to 119.99	390	Vertical
Tussock	37	0	6.00 to 10.99	434	Vertical
Tussock	38	1	6.00 to 10.99	426	Vertical
Tussock	39	2	6.00 to 10.99	395	Vertical
Tussock	40	0	90.00 to 119.99	493	Vertical
Tussock	41	1	90.00 to 119.99	431	Vertical
Tussock	42	2	120.00 to 149.99	390	Vertical
Tussock	43	0	60.00 to 89.99	434	Vertical
Tussock	44	1	60.00 to 89.99	426	Vertical
Tussock	45	2	60.00 to 89.99	395	Vertical
Tussock	46	0	60.00 to 89.99	493	Vertical
Tussock	47	1	40.00 to 59.99	431	Vertical
Tussock	48	2	90.00 to 119.99	390	Vertical
Tussock	49	0	60.00 to 89.99	434	Vertical
Tussock	50	1	90.00 to 119.99	426	Vertical
Tussock	51	2	60.00 to 89.99	395	Vertical
Tussock	52	0	60.00 to 89.99	493	Vertical
Tussock	53	1	90.00 to 119.99	431	Vertical
Tussock	54	2	60.00 to 89.99	390	Vertical
Tussock	55	1	40.00 to 59.99	431	Vertical

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

3.4.2 Hot Carbon Emissions

This experiment was designed to simulate hot carbon particles and hot exhaust gas exiting a vehicle exhaust. A few similar experiments have been conducted (Maxwell & Mohler, 1973; Kaminski, 1974; San Dimas EDC, 1980; Gonzales, 2008), but no standard procedure has been published. Therefore, pilot tests were conducted to determine the best method to test this ignition source, and to determine the most appropriate design. The hot carbon emissions experimental procedure represented a scenario involving a vehicle which had stopped off-road near fully cured grasses, and had remained in idle for five minutes. Hot carbon sparks (1.0 mm diameter) were pushed through a steel pipe and propelled onto the grass sample using hot air flow (200ºC at 3.7 m/s).

The specifications for this experiment were based on information gathered from a literature review (subsection 2.3.2, Chapter Two). Hot carbon particles can flake off the exhaust pipe of vehicles and exit the tailpipe or manifold as hot sparks when the engine is accelerated (Davis *et al.*, 1999). The 1.0 mm size of the hot carbon sparks represented a worst-case scenario of a vehicle with a poorly-maintained exhaust system, operating in off-road conditions. In New Zealand, it is advisable for off-road vehicles to have a spark arrester fitted; however, if the spark arrester is not maintained, particles as large as 12.7 mm may be ejected from the exhaust system (San Dimas EDC, 1980; Gonzales, 2003a; 2003b; Forest and Rural Fires Act 1977, 2008). Spark arresters are designed to trap particles larger than 0.58 mm in diameter. The 1.0 mm size used in this experiment could be trapped by a spark arrester; but the experiment was designed to simulate a faulty spark arrester in this scenario, or it was assumed that one was not fitted.

Hot air was set to approximately 200ºC and flowed at a constant speed of 3.69 m/s ± 0.01 s.e.. Temperature was measured by a 24-gauge type-K thermocouple, and was chosen to represent actual vehicle exhaust gas temperature, as derived from the work described in subsection 3.4.1 (Figure 3.8) and from Gonzales (2008). Hot air flow was measured by the Dantec hot wire sonic anemometer, positioned about 7 cm from the end of the experiment pipe. The Nissan Navara 2006 was used to compare 4WD utility vehicle exhaust air flow with laboratory hot air flow. With the engine idling, exhaust air flow varied between 5.60 and 5.75 m/s. Air flow speed could not be increased in the laboratory; however, this detail did not affect results because the hot air flow was used to propel hot carbon sparks onto the grass samples.

The experimental set-up consisted of the steel pipe, hot air, hot carbon sparks of 1.0 mm thickness, and the grass sample (Figures 3.13 and 3.14). The sample can was clamped into place on a retort stand and located approximately 7 cm from the end of the steel pipe. The top of the can was positioned about 2 cm below the end of the steel pipe to increase the chance of sparks landing on the grass sample. The steel pipe was 0.2 cm thick, 60.6 cm long, and 5.0 cm in diameter. A 1 x 1 cm hollow column was welded to an 8 x 8 cm funnel at one end of the pipe. A Bosch PHG 600CE Hot Air Gun simulated the hot exhaust gases, and was inserted into one end of the steel pipe. It was set to level two and adjusted so that air temperature exited the pipe at approximately 200°C. The hot carbon sparks were prepared by heating ordinary wood pellets until they glowed. This took less than a minute on a coiled nichrome resistance wire element, set to 570ºC (Figure 3.15). The average mass of each glowing wood pellet was 0.0370 g ± 0.0022 s.e.. Individual glowing pellets were crushed through a 1.0 mm sieve, which allowed sparks/particles to enter the pipe through the funnel and be pushed onto the grass sample by the hot air flow. The set-up was designed to be easily repeatable.

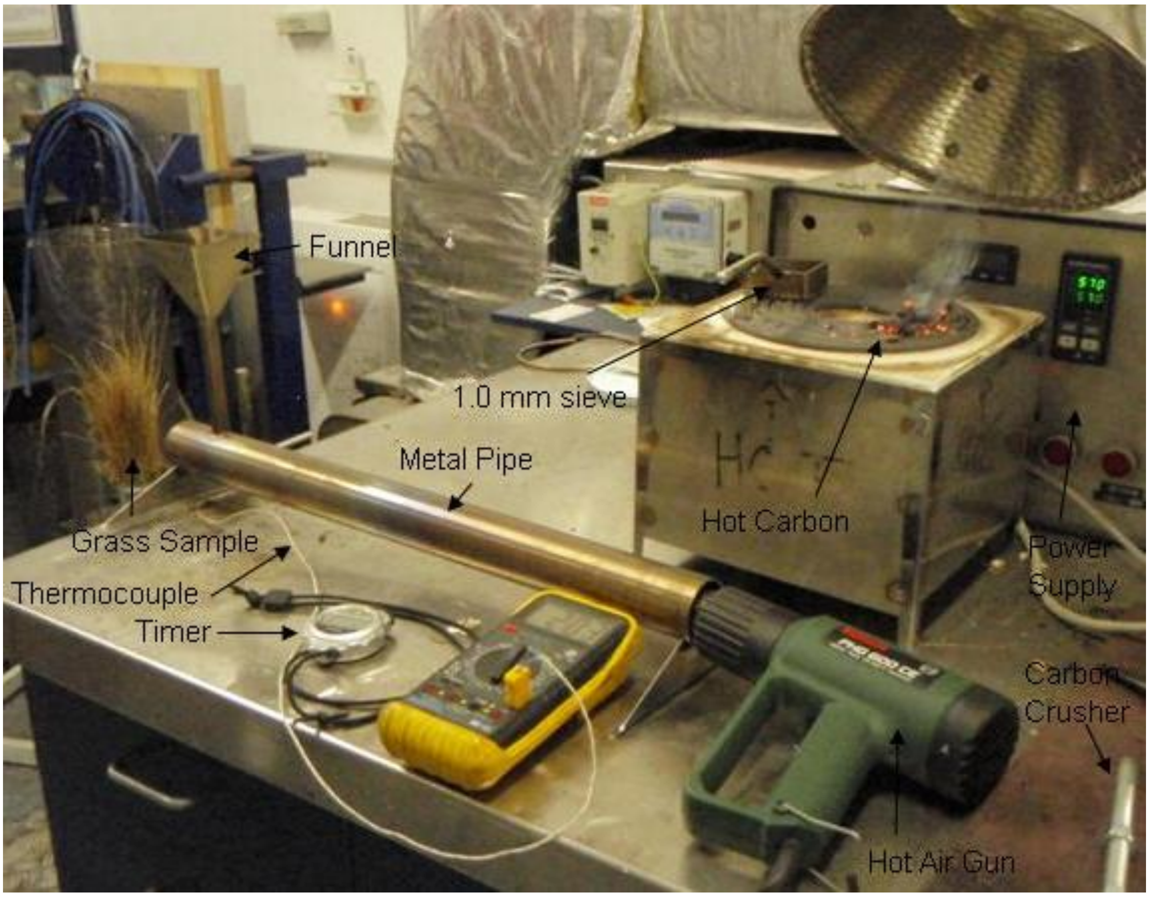

Figure 3.13 Carbon emissions experimental set-up.

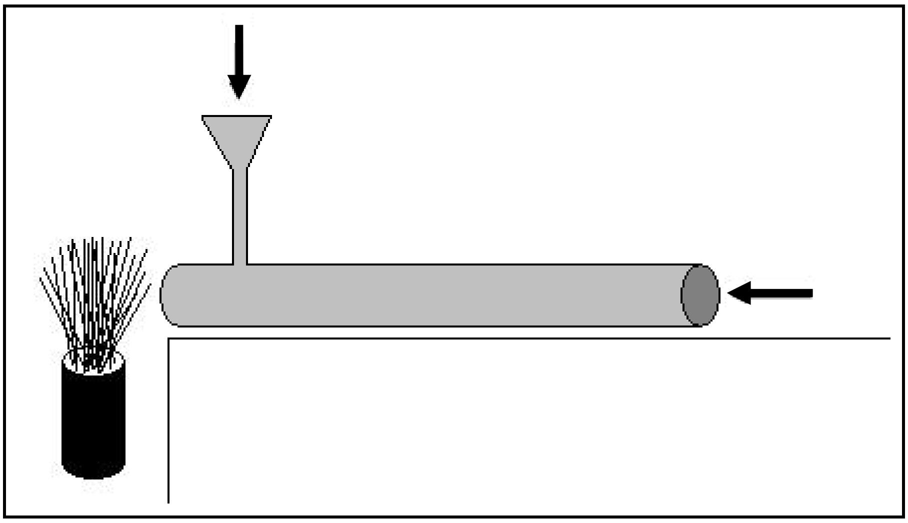

Figure 3.14 Schematic of the carbon emissions experimental set-up, with the downward facing arrow denoting hot carbon particle entry, and the horizontal arrow indicating air flow direction (not to scale).

Figure 3.15 The 1.0 mm sieve and wood pellets in glowing and original states.

Once the hot air flow had been calibrated, the grass sample was correctly positioned and timing began. After 30 seconds, a glowing wood pellet was pushed through the sieve into the funnel, and exited the steel pipe as sparks. This was repeated every 30 seconds for up to five minutes. Due to time constraints, trials were terminated after five minutes if no ignition occurred. However, the sample remained in place for a further 30 seconds in order to record observations.

There were nine trials for each grass type (Table 3.5). Three repetitions were completed per trial. Trials six to nine used the ‘moisture evaporation method’ to achieve different MC classes. Ignitions usually occurred if a spark landed on the sample in a favourable position. MC was increased to values above 150% for trial nine.

Table 3.5 Trial specifications for carbon emissions experiments.

Grass Type	Trial	Wind Speed (m/s)	Temperature at end of tail pipe (ºC)	MC class (%)
Tussock/Exotic*	1	3.69	200	16.00 to 22.99
Tussock/Exotic	2	3.69	200	11.00 to 15.99
Tussock/Exotic	3	3.69	200	6.00 to 10.99
Tussock/Exotic	4	3.69	200	3.00 to 5.99
Tussock/Exotic	5	3.69	200	0.00 to 2.99
Tussock	6	3.69	200	40.00 to 59.99
Exotic	6	3.69	200	60.00 to 89.99
Tussock	7	3.69	200	60.00 to 89.99
Exotic	7	3.69	200	90.00 to 119.99
Tussock/Exotic	8	3.69	200	120.00 to 149.99
Tussock	9	3.69	200	150.00 to 175.00
Exotic	9	3.69	200	120.00 to 149.99

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

3.4.3 Metal Sparks

As with carbon emissions, little work has been done to investigate the probability of ignition from metal sparks, and no standard testing procedure exists. The metal sparks experiment was designed to simulate hand-held grinding operations, or sparks produced by outdoor power equipment and machinery in the field. Pilot tests were conducted to determine an optimum testing method.

In the laboratory, a piece of steel was clamped into a vice on a workbench, and a 230 mm-Makita hand-held grinder (model GA9040S), with a surface speed of 80 m/s, was used to grind metal sparks onto the grass sample (Figures 3.16 and 3.17). The grass sample was clamped in place on a retort stand at a distance of approximately 1.0 m from the steel.

Figure 3.16 Metal sparks experimental set-up.

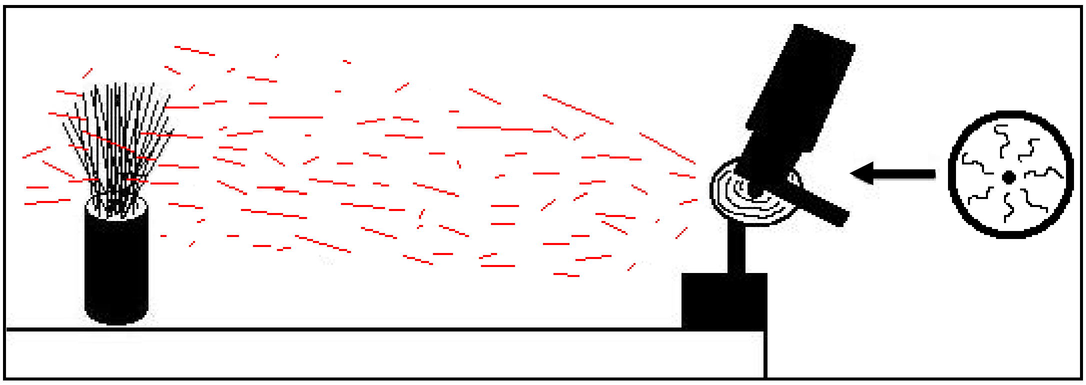

Figure 3.17 Schematic of the metal sparks experimental set-up, with an arrow indicating wind direction (not to scale).

Grinding lasted no more than 30 seconds. If ignition occurred, grinding stopped immediately. The appropriate ignition type (FI, GI, or NI), and time-to-ignition were recorded. The steel mass was recorded before and after each trial to quantify the mass of sparks from each grinding session. For tussock and exotic grass trials, the average metal mass grinded was 13.22 g ± 0.53 s.e., and 11.98 g ± 0.56 s.e. respectively. Some samples ignited relatively quickly, which explains the range of metal mass values reported.

Trials for this ignition source began with low MC classes and gradually increased to determine the ignition thresholds. When high MC classes were tested, an iterative process was used to ensure that many different MC values were tested. For each grass type, 27 trials were completed (Table 3.6).

Table 3.6 Trial specifications for metal spark experiments.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)
Tussock/Exotic*	1	0	16.00 to 22.99
Tussock/Exotic	2	1	16.00 to 22.99
Tussock/Exotic	3	2	16.00 to 22.99
Tussock/Exotic	4	0	11.00 to 15.99
Tussock/Exotic	5	1	11.00 to 15.99
Tussock/Exotic	6	2	11.00 to 15.99
Tussock/Exotic	7	0	6.00 to 10.99
Tussock/Exotic	8	1	6.00 to 10.99
Tussock/Exotic	9	2	6.00 to 10.99
Tussock/Exotic	10	0	3.00 to 5.99
Tussock/Exotic	11	1	3.00 to 5.99
Tussock/Exotic	12	2	3.00 to 5.99
Tussock/Exotic	13	0	0.00 to 2.99
Tussock/Exotic	14	1	0.00 to 2.99
Tussock/Exotic	15	2	0.00 to 2.99
Tussock	16	0	16.00 to 22.99
Exotic	16	0	60.00 to 89.99
Tussock/Exotic	17	1	60.00 to 89.99
Tussock	18	2	60.00 to 89.99
Exotic	18	2	90.00 to 119.99
Tussock	19	0	40.00 to 59.99
Exotic	19	0	90.00 to 119.99
Tussock	20	1	40.00 to 59.99
Exotic	20	1	60.00 to 89.99
Tussock/Exotic	21	2	90.00 to 119.99
Tussock	22	1	120.00 to 149.99
Exotic	22	1	60.00 to 89.99
Tussock	23	2	90.00 to 119.99
Exotic	23	2	40.00 to 59.99
Tussock	24	0	40.00 to 59.99

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

Table 3.6 Trial specifications for metal sparks experiments, cont.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)
Exotic	24	0	120.00 to 149.99
Tussock	25	1	90.00 to 119.99
Exotic	25	0	30.00 to 39.99
Tussock	26	2	90.00 to 119.99
Exotic	26	2	30.00 to 39.99
Tussock	27	0	90.00 to 119.99
Exotic	27	1	30.00 to 39.99

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

3.4.4 Organic Embers

Ignitions can occur from smouldering and flaming organic matter which has been trapped between hot vehicle parts, as reviewed in Chapter Two (Baxter, 2002; 2004). Some field experiments have investigated this type of ignition source, but no laboratory work has been conducted. Pilot testing helped to determine a favourable experiment method. The organic ember experimental procedure was designed to represent heated organic material which has fallen from a moving vehicle onto dead grass.

To create the organic embers, soil and grass was collected from Hakatere Conservation Park near Lake Clearwater (Figure 3.1). Care was taken to remove stones from the soil before mixing with grass and water to create soil disks. After several iterations, an optimum ratio of grass to soil was established, as described below.

Hot organic embers were simulated by heating the grass and soil disks to an average temperature of 400ºC ± 4 s.e.. The disks were designed to represent pieces of hot grass and mud that have become stuck in hot places of an operating vehicle, and fall onto grass fuels. They were created by mixing small (< 2 cm long) pieces of tussock and exotic grass together with soil, with water to bind the materials together. The ratio of grass to soil was 1:13.5 by weight. The disks were moulded in oven-safe ice cube trays and oven-dried for 10 hours at 40ºC (Figure 3.18). Once removed from the trays, they were stored in the laboratory for at least one week before testing. Disk dimensions were 2.8 cm in diameter, and 1.9 cm high.

The hot plate was set to 800ºC, which heated up the organic disks as quickly as possible; the disks became red-hot within one minute 30 seconds. At this time, disk temperature was measured by a 0.0254 cm-gauge type-K thermocouple and immediately placed atop the grass sample (Figures 3.18, 3.19, and 3.20). The embers were left in place for a maximum of five minutes, and classified according to ignition type (FI, GI, or NI).

Figure 3.18 A tussock sample with a disk placed on top (left) and organic embers (right).

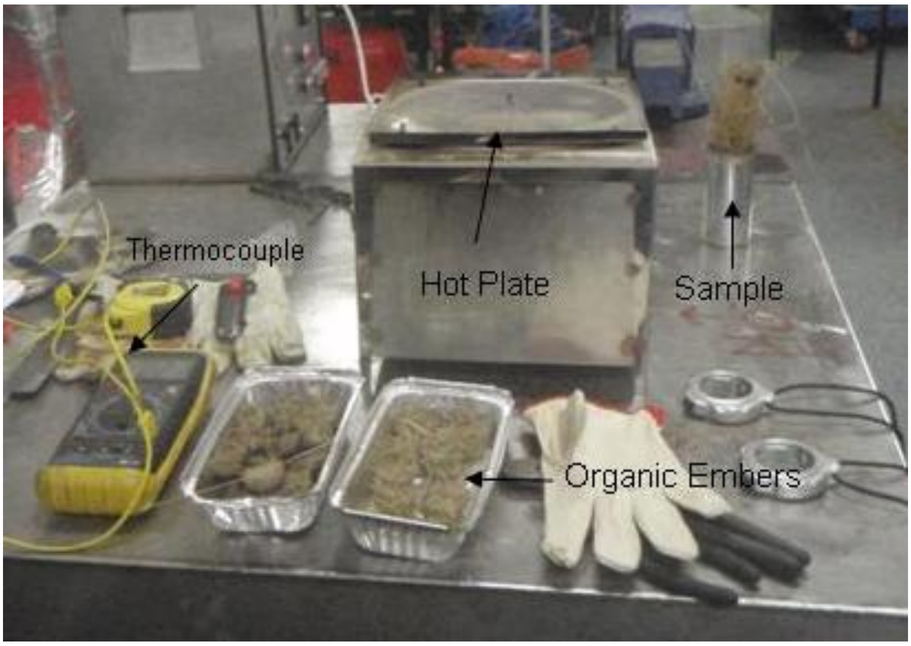

Figure 3.19 Organic ember experimental set-up.

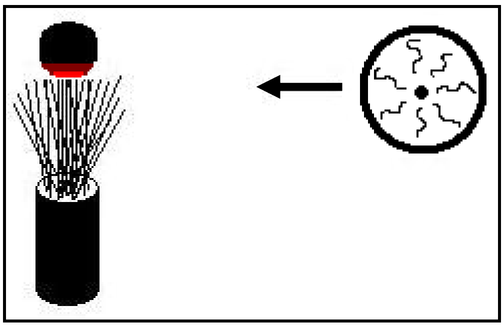

Figure 3.20 Schematic of the organic embers experimental set-up, with an arrow indicating wind direction (not to scale).

Trials for this ignition source commenced at the lowest MC class for tussock grass. For exotic grass samples, the trials commenced at the second lowest MC class (3.00 to 5.99%), because the available samples were in the 3.00 to 5.99% MC class at the time. No ignitions occurred for any of the trials, so three more trials were conducted at the lowest MC class for tussock samples. In total, six trials were carried out for each grass type (Table 3.7). No further trials were completed at higher MC classes due to the lack of ignitions.

Table 3.7 Trial specifications for organic embers experiments.

Grass Type	**Trial**	**Wind Speed (m/s)**	**MC class (%)**
Tussock	1	0	0.00 to 2.99
Tussock	2	1	0.00 to 2.99
Tussock	3	2	0.00 to 2.99
Exotic	1	0	3.00 to 5.99
Exotic	2	1	3.00 to 5.99
Exotic	3	2	3.00 to 5.99
Tussock/Exotic*	4	0	0.00 to 2.99
Tussock/Exotic	5	1	0.00 to 2.99
Tussock/Exotic	6	2	0.00 to 2.99

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

3.4.5 Open Flame

As reviewed in Chapter Two, open flames are produced by sources such as matches, cigarette lighters, barbeque lighters, gas cookers, camp fires, and candles. If flames are exposed to 100% cured grass, ignition is likely to occur at any MC as long as the flames are left in place for sufficient time. Flames heat up cured grass, drying it to its ignition point. The open flame experimental procedure was designed to represent careless use of an open flame, such as a gas cooker that has been knocked over and picked up again. Literature indicates that there are many ways of testing for the ignitibility of an open flame source, and the ignition thresholds depend on flame exposure time and MC (e.g., Babrauskas, 2003; de Groot *et al.*, 2005; Anderson & Anderson, 2010; Dimitrakopoulos *et al.*, 2010).

The experimental set-up consisted of the standard burner from an ISO 5756 ignition apparatus (ISO 5657, 1997), which was connected to a propane/butane gas mixture (Figures 3.21 and 3.22). Gas-flow was adjusted to produce about a 2.0 cm sized flame in still air. The sample can was clamped into place with a retort stand, so that the top of the can was approximately 2.5 cm below the flame position. A standard barbeque lighter was used to light the flame. Once the ignition apparatus was lit, the sample was moved into place. After 20 seconds, the flame was turned off and observations were classified according to ignition type (FI, GI, or NI).

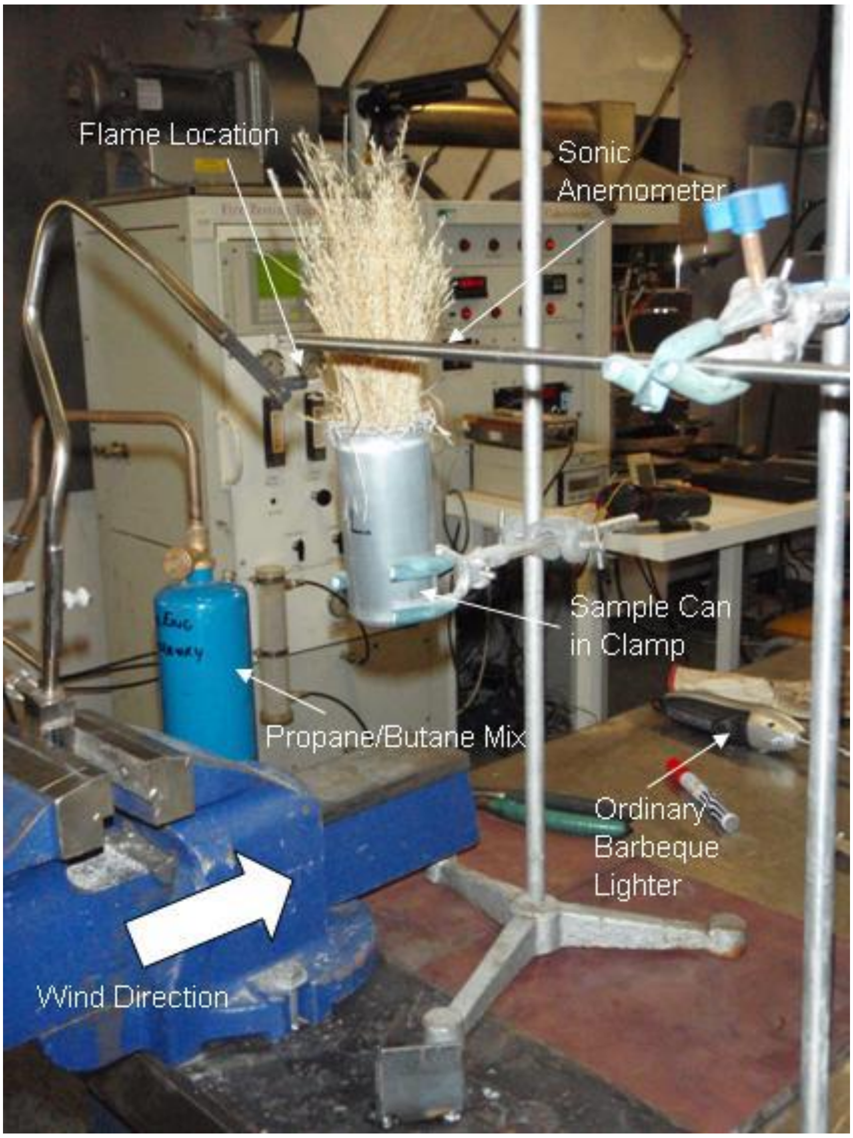

Figure 3.21 Open flame experimental set-up.

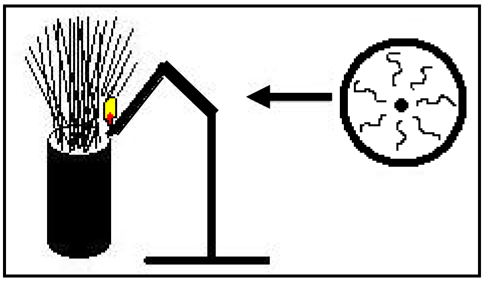

Figure 3.22 Schematic of the open flame experimental set-up, with an arrow indicating wind direction (not to scale).

Trials for this ignition source began with samples from the 11.00 to 15.99% MC class. MC values were increased after this class was tested, and an iterative process was used to condition the samples to high MC values. During trials 1-3 and 7-9, the MC was inconsistent because the 'moisture absorption/adsorption' method had not been developed properly, and moisture was unevenly distributed throughout the samples. Sample ends were extremely dry, and the middles were significantly wetter. The results from these trials were therefore excluded from the analyses. There were 21 trials for tussock grass, and 26 for exotic grass (Table 3.8).

Table 3.8 Trial specifications for open flame experiments.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)
Tussock/Exotic*	4	0	11.00 to 15.99
Tussock/Exotic	5	1	11.00 to 15.99
Tussock/Exotic	6	2	11.00 to 15.99
Tussock	10	0	16.00 to 22.99
Tussock	11	1	23.00 to 29.99
Tussock	12	2	23.00 to 29.99
Exotic	10	0	16.00 to 22.99
Exotic	11	1	16.00 to 22.99
Exotic	12	2	16.00 to 22.99
Tussock	13	0	11.00 to 15.99
Tussock	14	1	11.00 to 15.99
Tussock	15	2	16.00 to 22.99
Exotic	13	0	23.00 to 29.99
Exotic	14	1	16.00 to 22.99
Exotic	15	2	11.00 to 15.99
Tussock	16	0	40.00 to 59.99
Tussock	17	1	60.00 to 89.99
Tussock	18	2	30.00 to39.99
Exotic	16	0	120.00 to 149.99
Exotic	17	0	60.00 to 89.99
Exotic	18	1	60.00 to 89.99
Tussock	19	0	30.00 to 39.99
Tussock	20	1	60.00 to 89.99
Tussock	21	2	60.00 to 89.99
Exotic	19	0	6.00 to 10.99
Exotic	20	0	60.00 to 89.99
Exotic	21	1	90.00 to 119.99
Tussock	22	0	40.00 to 59.99
Tussock	23	1	23.00 to 29.99
Tussock	24	0	60.00 to 89.99
Exotic	22	2	60.00 to 89.99
Exotic	23	0	40.00 to 59.99
Exotic	24	1	90.00 to 119.99

* Tussock/Exotic refers to trials that were completed with the same specifications for both grass types

Table 3.8 Trial specifications for open flame experiments, cont.

Grass Type	Trial	Wind Speed (m/s)	MC class (%)
Tussock	25	1	60.00 to 89.99
Tussock	26	0	120.00 to 149.99
Tussock	27	0	90.00 to 119.99
Exotic	25	2	23.00 to 29.99
Exotic	26	0	60.00 to 89.99
Exotic	27	1	60.00 to 89.99
Exotic	28	2	40.00 to 59.99
Exotic	29	1	60.00 to 89.99
Exotic	30	2	40.00 to 59.99
Exotic	31	1	90.00 to 119.99
Exotic	32	2	90.00 to 119.99

* Tussock/Exotic refers to trials that w ere completed w ith the same specifications for both grass types

3.4.6 Summary of Laboratory Experiments

Each experiment was conducted in the same manner for each repetition, and included ambient temperature and RH records. Table 3.9 reports the total number of trials and repetitions conducted for each grass type and ignition source.

Table 3.9 Total number of laboratory experiments.

Ignition Source	Total Number of Trials		Total Number of Repetitions	
	Tussock	Exotic	Tussock	Exotic
Hot Metal	55	36	165	108
Carbon Emissions	9	9	27	27
Metal Sparks	27	27	81	81
Organic Embers	6	6	18	18
Open Flame	21	26	63	78
Total	118	104	354	312

3.5 Field Experiments

The purpose of the field experiments was to compare and validate laboratory results under field conditions. The field experiment took place on November 24, 2009, in the Lake Emma parking lot of Hakatere Conservation Park (E1446655º, N5167893º) (Figure 3.1). The parking lot was surrounded by short, live grass fuels (Figure 3.23). Experiments were completed for hot metal, hot carbon emissions, metal sparks, and open flame ignition sources. All environmental conditions were measured throughout the day, which aided data analysis. Ambient temperatures were above 20ºC, and RH was lower than 35% for most of the day. At experiment levels (which varied between approximately 11 and 125 cm), average wind speed was 1.1 m/s, and at the 10 m level it was 7.4 m/s. Field experiments were video recorded, and completed for both tussock and exotic grass samples.

Figure 3.23 Field experimental set-up area (Lake Emma parking lot).

Field samples were slightly larger than laboratory samples to ensure enough fuel was available for ignition; nevertheless, field sample densities were identical to laboratory sample densities. Metal paint cans of 6.9 cm diameter and 9.3 cm height (347.6 cm^3) were covered with a 1.2 x 1.2 cm wire mesh (Figure 3.24). Grass length was cut to not more than 25 cm before placing into cans. Average oven-dry weight of tussock and exotic samples were 21.7 g ± 0.1 s.e., and 9.1 g ± 0.1 s.e. respectively. In the laboratory, samples were assembled from previously collected fully-cured grass. On the morning of the field experiments, they were transported to site and exposed to ambient weather conditions for at least two hours before experiments commenced. This conditioned them to the same MC levels that would have existed for fully cured grass *in situ* (Figure 3.25). Each tested sample was accompanied by three associated samples that were not tested, and were used to determine the approximate MC of the tested sample. Associated samples were brought back to the laboratory and oven-dried for 48 hours at 105ºC.

Figure 3.24 Sample cans for field experiments.

Figure 3.25 Tussock and exotic samples exposed to field conditions (e.g., ambient temperature and RH).

3.5.1 Hot Metal Contact

This experiment was conducted using exhaust systems of the same 4WD Nissan Navara 2006, turbo diesel as was used for the exhaust system temperature measurements (subsection 3.4.1), and of a Honda Foreman 400 ATV. Thermocouples (24-gauge, K-type) were attached to different points on the exhaust systems in order to determine locations of the highest exhaust system temperatures. Each vehicle was used to test each grass type three times, for a total of six trials per vehicle.

The experimental procedure tested ignition from direct contact of the grass sample with the hottest part of the exhaust system. Before testing, the vehicles drove on gravel roads for approximately 18 minutes, with a data-logger recording exhaust temperatures. After the vehicles returned, they remained in idle during the experiments. The hottest point of the exhaust system was determined by the data-logger, and the samples were pushed up onto this point and held in place by hand. The temperature of the exhaust system at this point was recorded. Each experiment lasted for a maximum of five minutes, or until ignition occurred. The appropriate ignition type (FI, GI, or NI) was recorded as well as the time-to-ignition. The first trial using the 4WD Nissan, tested for ignition at a location immediately before the first muffler, but this was subsequently changed to the catalytic converter, as it was found to be a few degrees hotter. For ignition tests using the ATV, samples were placed at the manifold (Figure 3.26).

Figure 3.26 Ignition testing of an exotic sample at the manifold of the ATV.

3.5.2 Hot Carbon Emissions

This experiment used the same 4WD Nissan as was used for the hot metal experiment. It was conducted directly after each hot metal trial. The ATV was intended to be used for the same experiment; however, when the engine was accelerated, exhaust gas dislodged the grass samples from the cans, and blew the fuel away. Furthermore, the ATV backfired each time the engine was accelerated, posing safety concerns. The Nissan was revved up to 3000 RPM during each trial, which caused exhaust speed to increase from about 5.6 m/s at idle to 30.0 m/s. This did not cause the sample fuel to blow away. The ATV's exhaust speed was not measured, but was likely higher than 30.0 m/s. The experiment was repeated three times per grass type, for a total of six times.

Samples were exposed to hot exhaust gases for between 5.5 minutes, and 7.2 minutes (see Chapter Four for recorded values). Grass samples were held by hand about 4 cm away from the tailpipe, atop a stand that was constructed from stacked wooden blocks (Figure 3.27). After 30 seconds, and every 30 seconds thereafter, the engine was accelerated to encourage the expulsion of hot carbon pieces. The vehicle remained in idle for four minutes, or until ignition occurred. If ignition did not occur after four minutes, the sample was moved next to the stand and a glowing wood pellet was pushed through a 1.0 mm sieve to shower hot sparks over the sample. The sample was then returned atop the stand. This was repeated three times before the experiment was terminated due to time constraints. A thermocouple was located at the end of the tailpipe to measure exhaust temperature. The appropriate ignition type (FI, GI, or NI) was recorded as well as the time-to-ignition.

Figure 3.27 Carbon emission field experimental set-up.

3.5.3 Metal Sparks

This experiment used the same metal grinder that was used in the laboratory. The experiment was conducted five times for each fuel type, for a total of ten experiments. A piece of steel was grinded for 30 seconds in each case, and the sample was located on a retort stand 1 m from the grinder (Figure 3.28). The steel was weighed before and after to determine the mass of metal grinded. The appropriate ignition type (FI, GI, or NI) was recorded as well as the time-to-ignition.

Figure 3.28 Metal sparks field experimental set-up.

3.5.4 Organic Embers

Because no ignitions were observed in the laboratory experiments on organic embers, no experiments were conducted in the field for this ignition agent.

3.5.5 Open Flame

This experiment used the same set-up as in the laboratory. A total of ten experiments were conducted, five for each grass type. Grass samples were held on a retort stand and exposed to the open flame for a maximum of 20 seconds for each trial. The appropriate ignition type (FI, GI, or NI) was recorded as well as the time-to-ignition.

3.5.6 Summary of Field Experiments

The environmental conditions were ideal for the field experiments, with ambient temperatures, RH levels, and experiment-level wind speeds approximating those recorded during the laboratory experiments. Table 3.10 summarises the number of field experiments completed for each ignition source.

Table 3.10 Total number of field experiments.

Ignition Source	**Total Number of Trials**	
	Tussock	**Exotic**
Hot Metal - 4WD	3	3
Hot Metal - ATV	3	3
Carbon Emissions - 4WD	3	3
Metal Sparks	5	5
Open Flame	5	5

Chapter 4. Results

4.1 Introduction

This chapter presents the experimental results and methodology for data analysis. Models to predict ignition success were fitted to laboratory experimental data for all ignition sources except organic embers. None of the samples tested using organic embers ignited, therefore probability of ignition models were not fitted for this ignition source. In addition, field experimental outcomes are presented and compared with results from the laboratory experiments and their probability of ignition models.

4.2 Laboratory Experiments

Laboratory experiment results are presented in five sheets within one Microsoft® Office Excel® file (Appendix I). Each sheet contains data under the following headings: Grass Type, Trial, Repetition, Ambient Temperature (°C), Relative Humidity (%), Wind Speed or Air Flow (m/s), MC (%), Ignition Type (FI, GI or NI), Ignition Time (s), and Comments. Some ignition sources required extra variables. These included hot metal (Hot Plate Temperature (°C) and Orientation), hot carbon emissions (Temperature at End of Tail Pipe (°C)), metal sparks (Metal Mass Grinded (g)), and organic embers (Surface Temperature of Ember (°C)). The remainder of this section explains the procedure used for data analysis, and presents the models to predict ignition success.

4.2.1 Data Analysis

Before the experimental data were analysed, the observations were classified into two categories: success or failure, where success = 1, and failure = 0 (Table 4.1): 'Flaming Ignition' (FI) was classified as 1, and 'No Ignition' was classified as 0, with 'Glowing Ignition' classified as either 1 or 0 depending on the characteristics of the glowing fuel. Video recordings and laboratory notes were used for this classification.

Table 4.1 Criteria used to classify experiment observations for data analysis.

Ignition Type	Classification	Requirement
FI	1	Sample must have burned completely down to the top of the sample can, OR sample must have been flaming when the ignition source was removed, and have completely burned within 30 seconds.
NI	0	Sample either did not ignite at all, OR sample ignited but did not burn completely 30 seconds after the ignition source was removed.
GI	1 or 0	Classification was 1 if sample flamed within 2 minutes of the end of the trial, OR if the area of glowing fuel was larger than 5 mm in diameter. Classification was 0 if sample did not flame within 2 minutes of the end of the trial, OR if the area of glowing fuel was weak and did not exceed 5 mm diameter.

After the experimental data were classified into success or failure categories, they were used to model probability of ignition success using logistic regression, which is based on the 'odds' of flaming ignition occurring. Models were generated using the statistical program R (R, 2009). To determine the best model, the R syntax **glm** (general linear model) with **family=binomial** (indicating a dichotomous outcome) was used (Crawley, 2007). Equation 4.1 was the basic model:

$$P(y=1) = \frac{1}{1+e^{-(\beta_0 + \beta_1 X_1 + \dots + \beta_n X_n)}}$$

Equation 4.1

where y = process of ignition, P(y=1) was the probability of ignition success, $X_1, \ldots, X_n$ were predictor variables, and $\beta_0, \beta_1, \ldots, \beta_n$ were regression coefficients.

For each ignition experiment, different variables were used to create the models, so comparison between models is limited. Several predictor variables were treated as categorical variables for the analysis, including wind speed (which is referred to as wind), grass type, and hot plate orientation. A stepwise procedure used the Wald test (z-test), which calculated a chi-square statistic, to determine which variables were most significant for each model (Hosmer & Lemeshow, 2000; Garson, 2010). The Akaike Information Criterion (AIC) was used to compare significance strength and the goodness-of-fit of each model, where lower values indicated stronger significance. The predictor variables' strength of association were based on the Somers' D, and the Nagelkerke R^2 index, where higher values signified stronger association (Anderson, 2006; Harrell Jr., 2009; Garson, 2010).

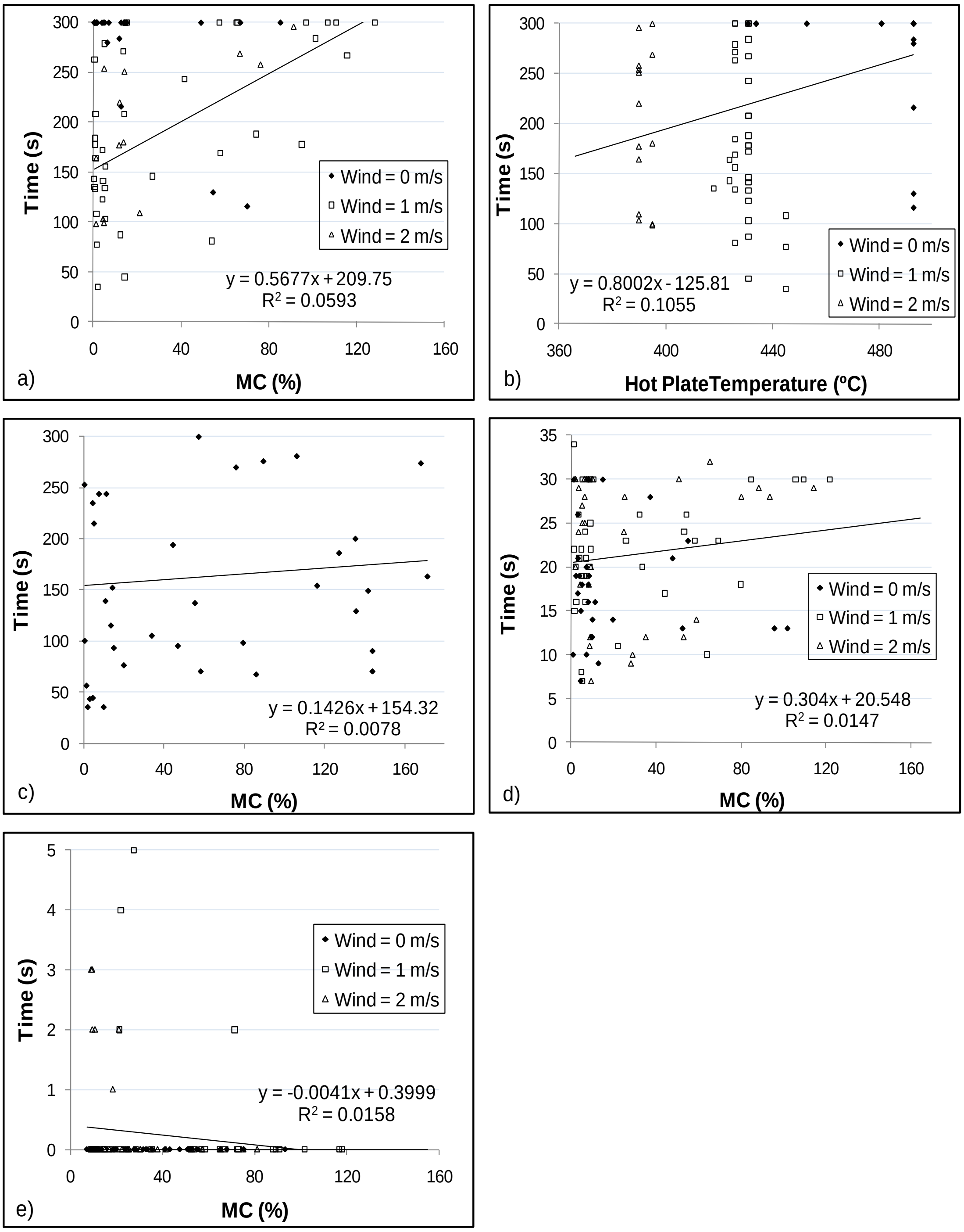

Figure 4.1 Relationships between time-to-ignition and MC or hot plate temperature for four tested ignition sources: a) hot metal (MC), b) hot metal (hot plate temperature), c) carbon emissions, d) metal sparks, and e) open flame.

Linear regression was used to test the relationship between MC and time-to-ignition. For hot metal, the relationship between hot metal temperature and time-to-ignition was also tested. Without considering the effect of wind speed, no significance was found for any ignition source, with all R^2 values less than 0.11 (Figure 4.1). For different wind speeds, analysis of time-to-ignition data resulted in similar R^2 values (Table 4.2). However for hot metal, the relationships between time-to-ignition and MC at different wind speeds were slightly stronger, with R^2 values ranging from 0.25 to 0.36. For open flame with a wind speed of 0 m/s, the relationship was not analysed because all ignitions were instantaneous (time-to-ignition = 0 s). No models are reported for the linear regression analyses due to the findings of low and non-significance. Exponential relationships between MC and time-to-ignition were also explored, and R^2 values were similar to those for linear regression, and thus are not reported.

Table 4.2 R^2 values from linear regression of time-to-ignition data for appropriate ignition sources and variables.

Ignition Source	Wind Speed (m/s)	Variable	R^2 Value
Hot Metal	0	MC	0.2497
Hot Metal	1	MC	0.3625
Hot Metal	2	MC	0.3494
Hot Metal	0	Hot Metal Temperature	0.0669
Hot Metal	1	Hot Metal Temperature	0.1122
Hot Metal	2	Hot Metal Temperature	0.0090
Carbon Emissions	3.7	MC	0.0078
Metal Sparks	0	MC	0.0232
Metal Sparks	1	MC	0.0779
Metal Sparks	2	MC	0.0165
Open Flame	1	MC	0.0113
Open Flame	2	MC	0.1767

4.2.2 Hot Metal

The MC of samples ranged from 0.50 to 152.35%. The experiments were conducted under conditions with an average ambient temperature of 22.3°C ± 0.1 s.e., and RH of 34.8% ± 0.3 s.e.. Hot metal temperatures ranged from 366 to 493ºC.

Model development commenced using the following predictor variables: MC, wind, ambient temperature, RH, grass type (tussock vs. exotic), metal temperature, and hot plate orientation (vertical vs. horizontal). Ambient temperature, RH, and grass type were not significant. The best model included predictor variables MC, wind, metal temperature, and hot plate orientation. When any of these predictor variables were dropped from the model, both fit and significance decreased. Table 4.3 contains the regression coefficient, the standard error, and the p-value associated with each variable. The p-value indicated that metal temperature was significant at least to the 1% level, and that MC, $wind_A$ (1 m/s), $wind_B$ (2 m/s), and horizontal orientation were highly significant to at least the 0.1% level. Model goodness-of-fit and predictor variables' strength of association are listed in Table 4.4. The AIC was slightly higher (by 1%) than a model including grass type; however, the standard errors were lower for all variables in this model. Furthermore, this model is slightly simpler in that it does not require differentiation for grass type.

Table 4.3 Regression coefficients, standard errors, and p-values associated with the predictor variables for the hot metal probability of ignition success model (n=273).

Statistical Test	Predictor Variables (X_n)					
	Intercept	MC (%)	$Wind_A$ (1 m/s)	$Wind_B$ (2 m/s)	Hot Plate Temperature (ºC)	Orientation (Horizontal)
Regression Coefficients (β_n)	-41.4958	-0.0223	1.2225	9.1142	0.0814	-2.5591
Standard Error	12.74	0.01	1.75	2.73	0.03	0.60
p-value	0.0011	0.0002	< 0.0001	0.0008	0.0016	< 0.0001

Table 4.4 Goodness-of-fit and strength of association values for the hot metal probability of ignition success model (n=273).

Statistical Test	Model Statistic
Akaike Information Criterion (AIC)	178.38
Somers' D	0.74
Nagelkerke R^2 index	0.42

Figure 4.2 presents six ignition probability curves as functions of hot metal temperature at a fuel MC of 1%. These curves represent the worst-case scenario where grass fuel is extremely dry. Without wind, ignition probabilities for both vertical and horizontal orientations are extremely low (< 0.2 for all experimental hot plate temperatures). Between the other four scenarios, the lowest hot plate ignition temperature occurred when grass was at a vertical orientation, with a wind speed of 2 m/s. This scenario poses a higher ignition risk for grass fuels than do the other scenarios. Additionally, the vertical orientation has lower hot plate ignition temperatures and poses a higher ignition risk for grass fuels than does the horizontal orientation. This finding was likely due to a higher level of contact between grass fuels and the surface of the vertically oriented hot plate.

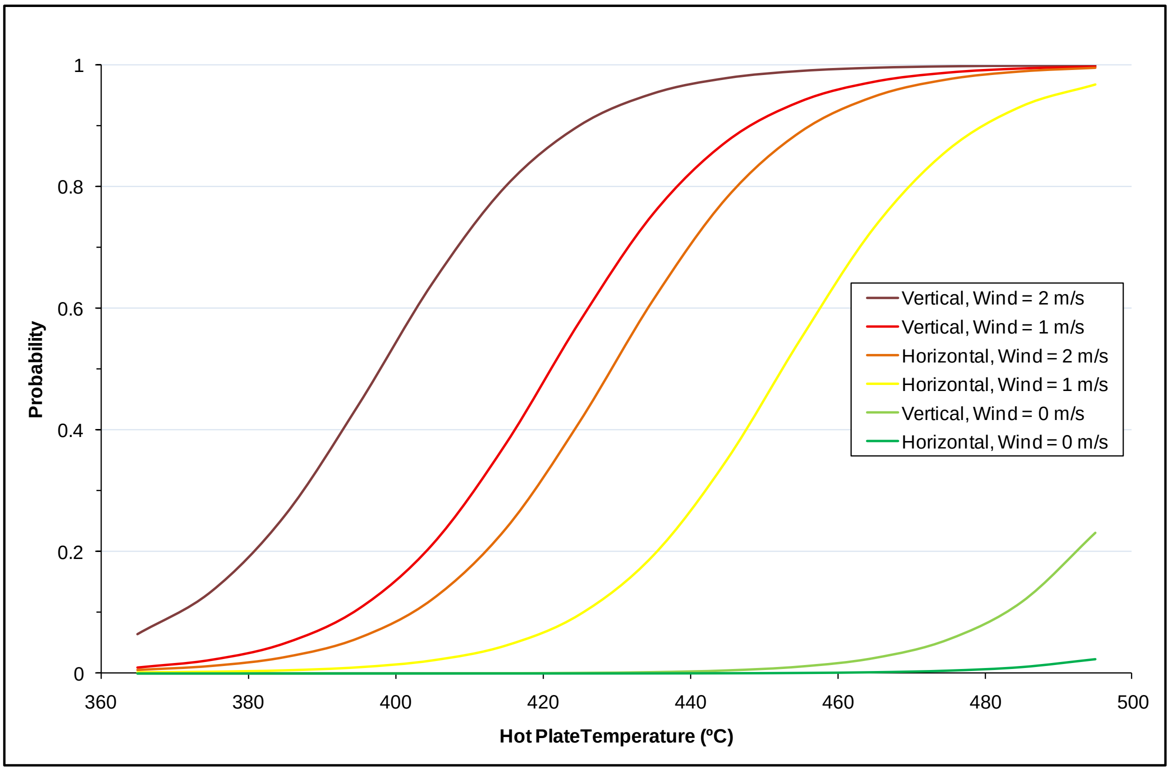

Figure 4.2 Plot of Equation 4.1 (using regression coefficients from Table 4.3) for six different scenarios tested in the laboratory, with MC set to 1%, to illustrate the probability of ignition success based on hot metal temperature.

Ignition thresholds were calculated for the four scenarios shown in Figure 4.2. A probability of 0.5 was used to determine the ignition thresholds, representing the boundary between success and failure at a MC of 1% (Table 4.5). Above the threshold levels, all ignitions would be predicted as successful, and below the threshold levels, they would be predicted as unsuccessful. As MC increases, so does the ignition temperature required for ignition. The lowest ignition temperature was 398ºC based on a vertical orientation and a wind speed of 2 m/s. Further discussion of these thresholds is contained in Chapter Five. When solving Equation 4.1 for $P(y = 1) = 0.5$, (based on the scenarios from Figure 4.2 and using predictor variables and regression coefficients from Table 4.3), 77% of the observations from the laboratory experiments were classified correctly.

Table 4.5 Ignition thresholds based on hot plate temperature and MC of 1%.

Scenario	Temperature Threshold Value (ºC), when MC = 1 %
Side, Wind = 2 m/s	398
Side, Wind = 1 m/s	421
Top, Wind = 2 m/s	429
Top, Wind = 1 m/s	452

Figure 4.3 shows how probability of ignition success increases as hot plate temperature increases. As fuel MC increases, the curve shifts to the right, and a higher temperature is required to achieve the same ignition probability values compared with lower MC levels. For simplicity, only two of the four scenarios (as described above) are shown here. The MC values represented MC at the time of initial contact between the fuel and the hot plate. Logically, the longer the fuel is in contact with the hot plate, the drier the fuel becomes, increasing ignition likelihood.

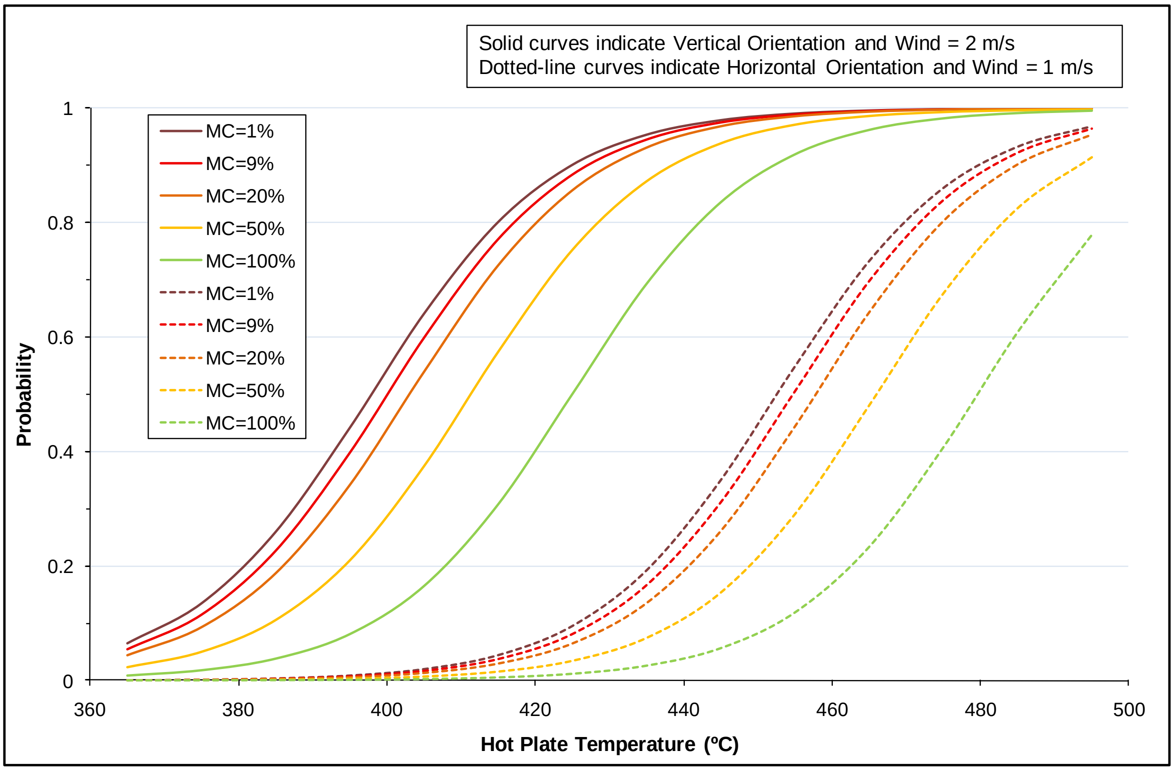

Figure 4.3 Probability of ignition success curves for hot plate temperature, based on various MC levels and two different scenarios (Vertical orientation and wind = 2 m/s; and Horizontal orientation and wind = 1 m/s).

4.2.3 Hot Carbon Emissions

The MC of samples ranged from 0.54 to 171.46%. The experiments were conducted under conditions with an average ambient temperature of 19.4°C ± 0.1 s.e., and RH of 41.1% ± 0.9 s.e..

Model development commenced using the following predictor variables: MC, ambient temperature, RH, and grass type. Grass type was excluded because it was only slightly significant (p-value = 0.0315). Two models were found to be significant, and Table 4.6 contains the regression coefficient, the standard error, and the p-value associated with each variable. The secondary model contained MC, ambient temperature, and RH; but, ambient temperature and RH were kept relatively constant throughout the experiment, so the use of this model is limited to the laboratory ambient conditions. The p-value indicated that MC was highly significant to at least the 0.1% level, and that ambient temperature and RH were significant to at least the 1% level. The single-variable model, based on MC only, was the preferred model, as it can be used to guide management decisions for a wider range of ambient temperature and RH levels. The p-value indicated that MC was significant to at least the 1% level. The p-value associated with MC of the secondary model was only marginally lower (0.009 vs. 0.0019), and the standard error was the same (Table 4.6).

Table 4.6 Regression coefficients, standard errors, and p-values associated with the predictor variables for the carbon emissions probability of ignition success models (n=54).

Statistical Test	**Predictor Variables (X_n)**		**Predictor Variables (X_n)**			
	Preferred Model		Secondary Model			
	Intercept	MC (%)	Intercept	MC (%)	Ambient Temperature (ºC)	RH (%)
Regression Coefficients (β_n)	1.1875	-0.0183	-76.9533	-0.0339	4.4104	-0.1581
Standard Error	0.44	0.01	30.96	0.01	1.67	0.06
p-value	0.0069	0.0019	0.0129	0.0009	0.0084	0.0083

The secondary model was stronger than the preferred model, as indicated by a 23% higher AIC value, and by higher predictor variables' strength of association (Table 4.7). Under favourable environmental conditions that match the range of ambient temperature and RH conditions from the laboratory experiments, it should be used in place of the preferred model.

Table 4.7 Goodness-of-fit and strength of association for the carbon emissions probability of ignition success models (n=54).

Statistical Test	**Model Statistic**	
	Preferred Model (with MC only)	Secondary Model (with predictor variables MC, Ambient Temperature, and RH)
Akaike Information Criterion (AIC)	66.57	51.09
Somers' D	0.46	0.78
Nagelkerke R^2 index	0.27	0.59

Ignition thresholds were determined for both models by solving Equation 4.1, using regression coefficients from Table 4.6, for MC when P(y = 1) = 0.5. For the preferred model, the threshold was determined to be approximately 65% MC, defining the boundary between ignition success and failure; therefore, when MC levels are above 65%, all ignitions are predicted as unsuccessful, and when MC levels are below 65% all ignitions are predicted as successful. Figure 4.4 shows the experimental observations classified into ignition success or failure, with the probability of ignition success curve, and the boundary between ignition success and failure. Many of the observations were classified correctly (69%). For the secondary model, the threshold was determined to be approximately 62% MC, with average ambient temperature of 19.4ºC and average RH of 41.1%. Figure 4.5 shows the experimental observations classified into ignition success or failure, with the probability of ignition success curve, and the boundary between ignition success and failure. Most of the observations were classified correctly (78%).

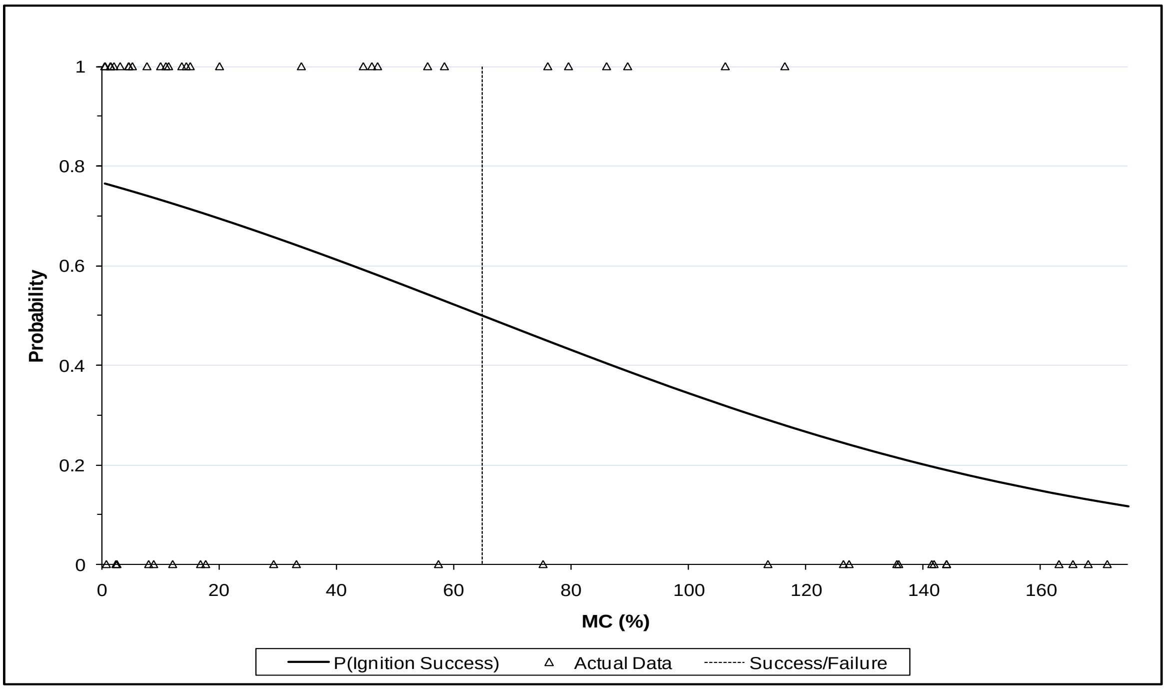

Figure 4.4 Plot of carbon emissions experimental data (categorised into success or failure), with the probability curve from Equation 4.1 using regression coefficients from the best model (Table 4.6), and the line indicating the boundary for success/failure based on P(y = 1) = 0.5.

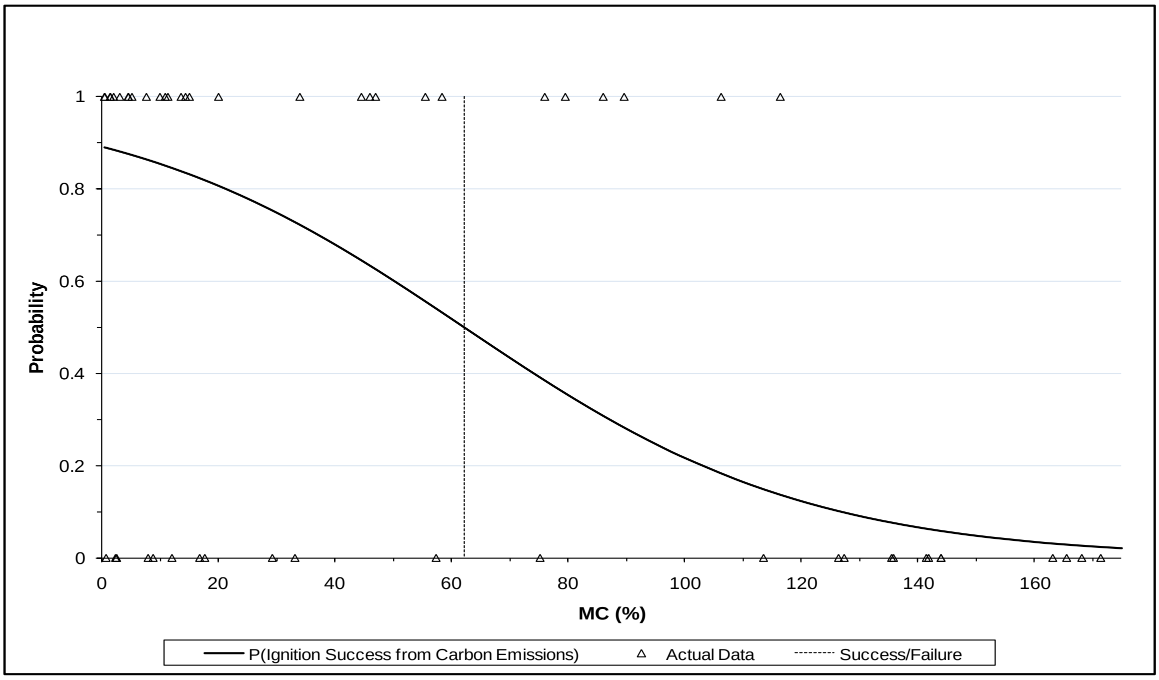

Figure 4.5 Plot of carbon emissions experimental data (categorised into success or failure), with the probability curve from Equation 4.1 using regression coefficients from the secondary model (Table 4.6) with average ambient temperature 19.4ºC and average RH 41.1%, and the line indicating the boundary for success/failure based on P(y = 1) = 0.5.

4.2.4 Metal Sparks

The MC of samples ranged from 0.97 to 164.42%. The experiments were conducted under conditions with an average ambient temperature of 21.8°C ± 0.10 s.e., and RH of 34.4% ± 0.3 s.e..

Model development commenced using the following predictor variables: MC, wind, ambient temperature, RH, grass type, and metal mass grinded. Wind, ambient temperature, RH, and grass type were not significant. Two models were compared for significance strength and goodness-of-fit, as they were both highly significant. The single-variable model, based on MC, was the best model. The discarded model contained MC and metal mass grinded. The discarded model was rejected for several reasons:

1) it only provided a marginally better fit than the single-variable model (Table 4.8);
2) the standard error and p-values were slightly higher than the best model (Table 4.9);
3) the two variables were highly correlated (r = 0.57, p = < 0.0001);
4) it required users to input the mass of metal grinded, but usually this value cannot be measured in the field, e.g. train tracks cannot be weighed before and after grinding.

The best model's p-values indicated that MC was significant to at least the 1% level (Table 4.9).

Table 4.8 Goodness-of-fit and strength of association for the metal sparks probability of ignition success models (n=162).

Statistical Test	**Model Statistic**	
	Best Model (with MC only)	Discarded Model (with predictor variables MC, and Metal Mass Grinded)
Akaike Information Criterion	101.58	90.85
Somers' D	0.85	0.91
Nagelkerke R^2 index	0.72	0.77

Table 4.9 Regression coefficients, standard errors, and p-values associated with the predictor variables for the metal sparks probability of ignition success models (n=162).

Statistical Test	**Predictor Variables (X_n)**		**Predictor Variables (X_n)**		
	Best Model		Discarded Model		
	Intercept	MC (%)	Intercept	MC (%)	Metal Mass Grinded (g)
Regression Coefficients (β_n)	2.8132	-0.0762	5.4866	-0.0649	-0.2468
Standard Error	0.42	0.01	1.01	0.01	0.07
p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0009

The ignition threshold was determined by solving Equation 4.1, using the regression coefficients from the best model (Table 4.9), for MC when P(y = 1) = 0.5. This threshold was determined to be approximately 37% MC, defining the boundary between ignition success and failure. Figure 4.6 shows the experimental observations classified into ignition success or failure, with the probability of ignition success curve, and the boundary between ignition success and failure. Most of the observations were classified correctly (90%).

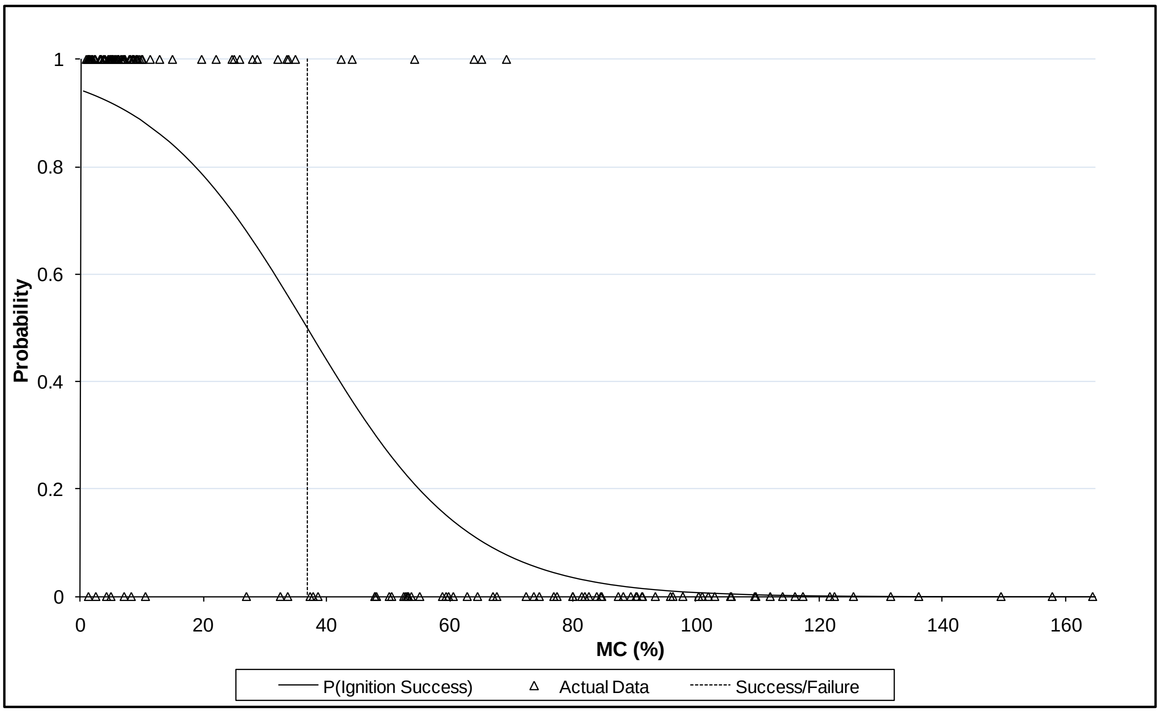

Figure 4.6 Plot of metal sparks experimental data (categorised into success or failure), showing the probability curve from Equation 4.1 using regression coefficients from the best model (Table 4.9), and the line indicating the boundary for success/failure based on P(y = 1) = 0.5.

4.2.5 Organic Embers

All of the 36 tests carried out with organic embers were classified as unsuccessful ignitions. However, a tussock sample at a MC of 0.54% glowed for three seconds after a 406°C ember was placed on it, and then it self-extinguished. This was the only sample that exhibited any signs of ignition potential. It was therefore not possible to develop an ignition probability model for this ignition source.

Results indicated that there was very low to no probability of ignition from the hot organic embers that were used in the laboratory. These laboratory experiments were carried out under the following average conditions: ambient temperature of 23.6 ± 0.4 s.e., RH of

36.8 ± 0.6 s.e., wind speeds equal to or less than 2 m/s, an ember surface temperature of 400.6°C ± 3.6 s.e., and at MC values less than 2%. This result does not imply that other types of hot organic embers would have the same low probability igniting dry grass.

4.2.6 Open Flame

The MC of samples ranged from 7.31 to 155.35%. The experiments were conducted under conditions with an average ambient temperature of 21.2°C ± 0.1 s.e., and RH of 31.8% ± 0.2 s.e..

Model development commenced using the following predictor variables: MC, wind, ambient temperature, RH, and grass type. Only MC and wind were found to be significant predictor variables. Wind (2 m/s) was not significant (p-value = 0.7874), which was most likely due to this higher wind speed repeatedly blowing out the experimental flame (refer to Chapter Five for further discussion). The best model included MC and wind (0 and 1 m/s). The single-variable model, based on MC, was discarded. Table 4.10 contains the regression coefficient, the standard error, and the p-value associated with each variable. The p-values indicated that all predictor variables were significant to at least the 1% level. The goodness-of-fit and predictor variables' strength of association are listed in Table 4.11. Both models were highly significant, but the best model had a much higher goodness-of-fit (AIC = 39.87 compared with 64.47), and a lower standard error associated with MC. Also, the number of experimental observations classified correctly was higher for the preferred model (97% compared with 89%).

Table 4.10 Regression coefficients, standard errors, and p-values associated with the predictor variables for the open flame probability of ignition success models (n=141).

Statistical Test	**Predictor Variables (X_n)**			**Predictor Variables (X_n)**	
	Best Model			Discarded Model	
	Intercept	MC (%)	Wind (1 m/s)	Intercept	MC (%)
Regression Coefficients (β_n)	8.2324	-0.2972	8.2313	4.8882	-0.1388
Standard Error	2.23	0.08	2.46	0.86	0.02
p-value	0.0002	< 0.0001	0.0008	< 0.0001	< 0.0001

Table 4.11 Goodness-of-fit and strength of association for the open flame probability of ignition success models (n=141).

Statistical Test	**Model Statistic**	
	Best Model (with predictor variables MC, and wind (0 m/s and 1 m/s))	Discarded Model (with MC only)
Akaike Information Criterion (AIC)	39.87	64.47
Somers' D	0.98	0.95
Nagelkerke R^2 index	0.91	0.82

Ignition thresholds for open flame were determined by solving Equation 4.1, using the regression coefficients from the best model (Table 4.10), for MC when P(y = 1) = 0.5, which defined the boundary between ignition success and failure. The threshold was calculated for the two significant wind categories (no wind, and wind = 1m/s). Without wind, the ignition threshold was 28% MC. Figure 4.7 shows the experimental observations without wind, classified into ignition success or failure, with the probability of ignition success curve, and the boundary between ignition success and failure. Almost all observations were classified correctly (94%). With wind at 1 m/s, the ignition threshold was 55% (Figure 4.8). All observations were classified correctly (100%). Including both wind levels, 97% of the observations were classified correctly, as previously mentioned.

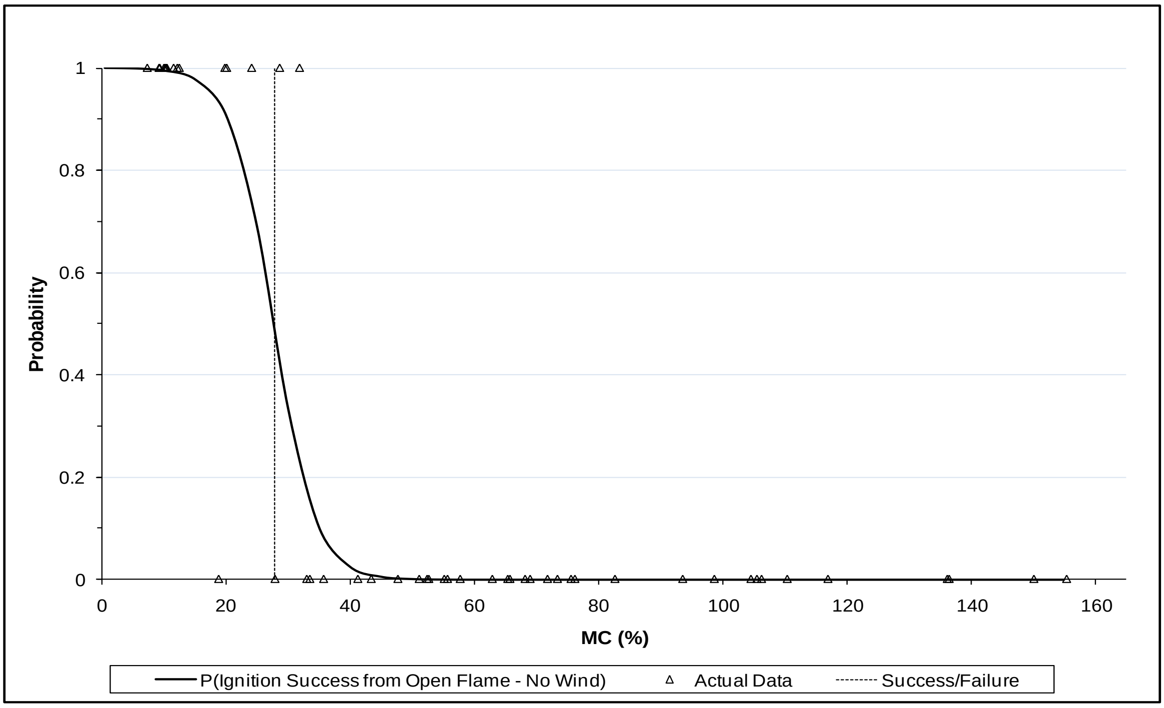

Figure 4.7 Plot of open flame experimental data without wind (categorised into success or failure), with the probability curve from Equation 4.1 using regression coefficients from the best model (Table 4.10), and the line indicating the boundary for success/failure based on $P(y = 1) = 0.5$.

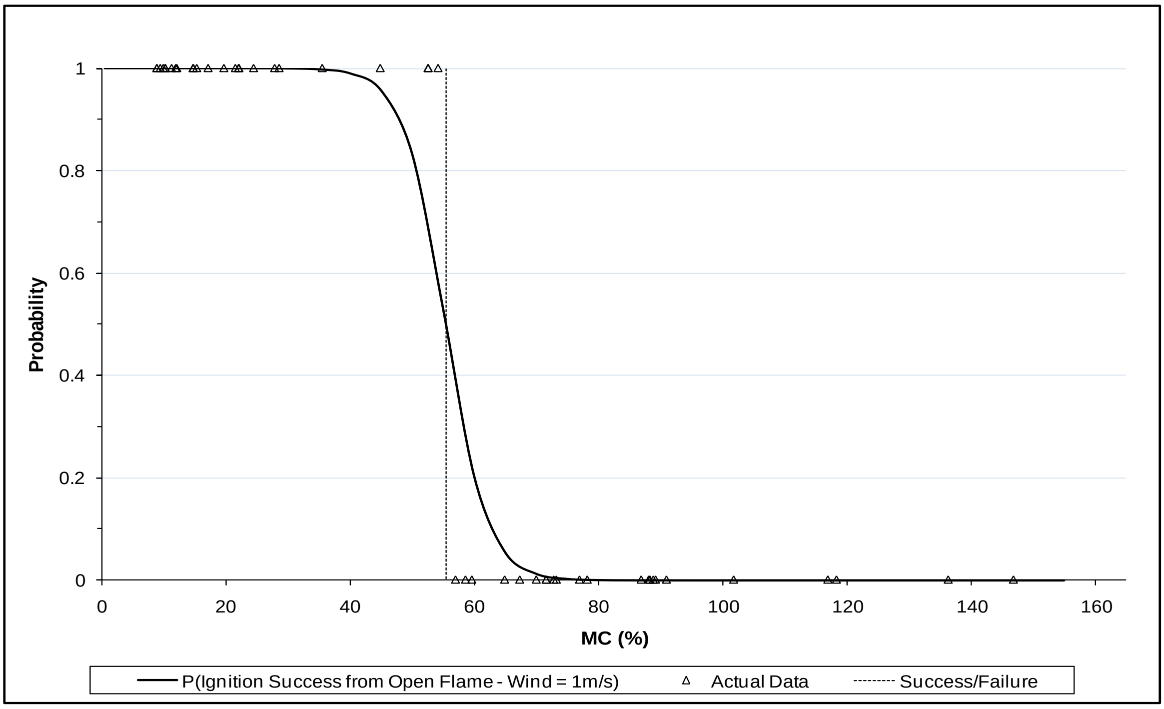

Figure 4.8 Plot of open flame experiment data with wind = 1 m/s (categorised into success or failure), with the probability curve from Equation 4.1 using regression coefficients from the best model (Table 4.10), and the line indicating the boundary for success/failure based on $P(y = 1) = 0.5$.

4.3 Field Experiments

Field experimental results are presented in the following subsections for each ignition source tested. Results were compared with predictions using the models derived from the laboratory experiments. Field experiments were conducted between 1000 to 1900 hrs, and average environmental conditions at the field site were: ambient temperature measured at 0.9 m height 19.4ºC ± 0.3 s.e., RH 39.7% ± 1.7 s.e., and wind speed at fuel level (which varied between 0.1 and 1.3 m height) 1.1 m/s ± 0.1 s.e.. Average conditions were recorded between the same hours at the Hakatere automatic weather station, located at E1451021º, N5169980º, 4.8 km NE of the field experiment site: ambient temperature 18.6ºC ± 0.9 s.e., RH 35.1% ± 4.2 s.e., and wind speed measured at 10 m height 7.4 m/s ± 0.7 s.e.. The height of the wind measurements was different to those at the experiment site. Ambient temperature and RH were considered to be comparable between the weather station and the field site.

Linear regression was used to test the relationship between MC and time-to-ignition for ignition sources that caused successful ignitions (hot metal (ATV) and metal sparks). However, the sample sizes were small ($n \leq 10$) and model outcomes were questionable. Models were therefore not reported for these analyses.

4.3.1 Hot Metal Contact

Results for the hot metal field experiments are summarised in Table 4.1. MC ranged from 10.2 to 15.7%. Throughout the experiments average ambient temperature and RH were 21.1ºC ± 0.3 s.e., and 32.4% ± 2.7 s.e. respectively. These conditions were similar to those for the laboratory experiments (averages of 22.3ºC and 34.8%). The average wind speed at experiment level was 1.1 m/s ± 0.1 s.e.. The tops and sides of grass samples were in contact with hot exhaust systems of the Nissan Navara 2006, 4WD turbo diesel (as previously used for temperature measurements (Chapter Three)), and of the Honda Foreman 400 ATV. The samples were located on hot round metal parts of the exhaust systems, comprising a combination of horizontal and vertical orientations; whereas, in the laboratory, they were located on hot flat metal, comprising two separate tests in horizontal and vertical orientations. Field test findings were compared with findings from the vertical hot metal orientations in the laboratory, because there was full contact between the tops and sides of grass fuels, and the logistic regression model predicted probabilities of ignition at lower temperatures compared with the horizontal orientation (subsection 4.2.2). Equation 4.1, with regression coefficients from Table 4.3, was used to calculate probability values for the MC levels and hot metal temperatures measured during the field experiments. Wind speed was set to 1 or 2 m/s depending on the field experiments' average wind speed (Tables 4.12 and 4.13).

Table 4.12 Field experimental results for direct hot metal contact with exhaust systems of the Nissan Navara (UTE) and the Honda Foreman (ATV).

Grass Type	Trial	Vehicle	Time	Ambient Temperature (°C)	RH (%)	Average Wind Speed at Experiment Level (m/s)	Average Fuel Moisture Content (%)	Exhaust System Metal Temperature (°C)	Drive Time (min)	Ignition Type	Ignition Time (s)
Tussock	1	UTE	11:41	21.1	24.2	1.67	11.5	218	19	NI	~
Tussock	2	UTE	12:53	21.5	24.2	1.19	10.7	220	20	NI	~
Tussock	3	UTE	13:41	21.7	33.7	0.89	10.2	215	20	NI	~
Exotic	1	UTE	14:26	21.0	33.7	1.08	15.4	214	23	NI	~
Exotic	2	UTE	15:08	21.9	30.3	1.59	13.8	213	20	NI	~
Exotic	3	UTE	15:54	19.4	49.0	0.96	15.4	229	17	NI	~
Tussock	4	ATV	12:32	21.3	24.2	1.51	11.0	427	19	FI	27
Tussock	5	ATV	13:17	21.8	23.7	1.33	10.7	480	17.5	FI	102
Tussock	6	ATV	14:04	22.1	25.4	0.55	10.2	467	18	FI	61
Exotic	4	ATV	14:49	21.7	33.7	0.82	15.0	462	23	FI	72
Exotic	5	ATV	15:29	21.6	36.2	0.52	13.5	512	17	FI	105
Exotic	6	ATV	16:25	18.3	50.3	0.66	15.7	465	55	FI	16
			Average	21.12	32.38	1.06	12.76	UTE = 218.2 ATV = 468.8	22.4		63.8
			Standard Error	0.33	2.68	0.12	0.65	UTE = 2.4 ATV = 11.3	3.0		15.1

Table 4.13 Probability predictions for the hot metal field experimental observations using Equation 4.1, with regression coefficients from Table 4.3.

Grass Type	Trial	Vehicle	Predictor Variables					Probability (P(y=1))
			MC (%)	$Wind_A$ (1 m/s)	$Wind_B$ (2 m/s)	Hot Metal Temperature (°C)	Orientation (Horizontal = 1, Vertical = 0)	
Tussock	1	UTE	11.5	0	1	218	0	0
Tussock	2	UTE	10.7	1	0	220	0	0
Tussock	3	UTE	10.2	1	0	215	0	0
Exotic	1	UTE	15.4	1	0	214	0	0
Exotic	2	UTE	13.8	0	1	213	0	0
Exotic	3	UTE	15.4	1	0	229	0	0
Tussock	4	ATV	11.0	0	1	427	0	0.90
Tussock	5	ATV	10.7	1	0	480	0	0.99
Tussock	6	ATV	10.2	1	0	467	0	0.97
Exotic	4	ATV	15.0	1	0	462	0	0.95
Exotic	5	ATV	13.5	1	0	512	0	1.00
Exotic	6	ATV	15.7	1	0	465	0	0.96

The average exhaust system temperature for the Nissan Navara (UTE) was 218ºC ± 2 s.e. (Table 4.1), which was lower than any metal temperature used in the laboratory. The circuit drive time ranged from 17 to 23 minutes, which was long enough to heat the exhaust system to its full potential, given the average road conditions and the fact that the vehicle was unloaded. However, the exhaust system had the potential to get much hotter if the engine had been working harder in a situation involving a fully loaded vehicle and rough terrain. All samples tested on the UTE's exhaust system did not ignite, and these failed ignitions were correctly predicted by the model (Table 4.13).

The average manifold temperature for the Honda Foreman (ATV) was 469ºC ± 11 s.e. (Table 4.1), which was within the range tested in the laboratory. The circuit drive time ranged from 17 to 23 minutes, except for one trial (Exotic grass, Trial 6) where it lasted 55 minutes. This was due to some organisational problems; however, the manifold temperature was comparable with the other drive times (465ºC). This suggests that the circuit drive times were long enough to heat the manifold to its full potential; but, a fully loaded ATV, towing a trailer over hilly terrain has the potential to result in hotter exhaust system temperatures. All samples tested on the ATV's manifold ignited, and these successful ignitions were correctly predicted by the model (Table 4.13). Further discussion on this experiment is contained in Chapter Five.

4.3.2 Hot Carbon Emissions

Results for the carbon emissions field experiments are summarised in Table 4.1. MC ranged from 9.9 to 14.0%. Throughout the experiments average ambient temperature, RH, and wind speed were 21.1ºC ± 0.5 s.e., 30.9% ± 4.3 s.e., and 1.0 m/s ± 0.1 s.e. respectively. Average ambient temperature and wind speed were very similar to the laboratory experiments (19.4ºC average, and 1 m/s), but average RH was much lower (30.9 vs. 41.1%). Average exhaust gas temperature was 105ºC ± 3 s.e., a considerable difference from the laboratory experiments (200ºC).

None of the samples ignited from the combination of hot exhaust gas and showers of 1.0 mm diameter sparks (Table 4.1). The probability model (Equation 4.1, using regression coefficients from the best model (Table 4.6)) predicted all observations to be successful. However, results from the laboratory and field experiments cannot be easily compared, since the exhaust gas temperature in the field did not reach the same temperature as the hot air flow did in the laboratory (105 vs. 200ºC). Further discussion on this experiment is contained in Chapter Five.

Table 4.14 Field experimental results for carbon emissions from the UTE (Nissan Navara).

Grass Type	Trial	Vehicle	Time	Ambient Temperature (ºC)	RH (%)	Average Wind Speed at Experiment Level (m/s)	Average Moisture Content (%)	Approximate Temperature at End of Tail Pipe (ºC)	Drive Time (min)	Ignition Type
Tussock	1	UTE	11:50	21.2	24.4	1.53	11.6	115	19	NI
Tussock	2	UTE	13:01	21.5	24.1	1.14	10.0	98	20	NI
Tussock	3	UTE	13:50	22.1	22.4	0.72	9.9	102	20	NI
Exotic	1	UTE	14:36	21.7	33.7	1.06	13.7	95	23	NI
Exotic	2	UTE	15:18	21.8	30.1	1.08	12.6	112	20	NI
Exotic	3	UTE	16:11	18.5	50.4	0.72	14.0	108	17	NI
			Average	21.13	30.85	1.04	11.97	105.0	19.8	
			Standard Error	0.54	4.28	0.12	0.73	3.2	0.8	

Table 4.15 Field experimental results for metal sparks.

Grass Type	Trial	Time	Ambient Temperature (ºC)	RH (%)	Average Wind Speed at Experiment Level (m/s)	Average Moisture Content (%)	Metal Mass Grinded (g)	Ignition Type	Ignition Time (s)
Tussock	1	16:59	18.5	49.2	0.50	9.7	25.9	FI	23
Tussock	2	17:06	18.5	49.2	0.86	10.9	13.1	FI	13
Tussock	3	17:11	18.2	49.8	1.67	9.2	11.2	FI	15
Tussock	4	17:16	18.2	49.8	1.32	10.0	12.6	FI	12
Tussock	5	17:21	18.0	51.0	1.84	10.3	12.8	FI	12
Exotic	1	17:04	18.5	49.2	0.65	11.3	5.6	FI	7
Exotic	2	17:09	18.2	49.8	1.01	13.0	5.3	FI	6
Exotic	3	17:14	18.2	49.8	1.50	11.2	3.2	FI	5
Exotic	4	17:19	18.0	51.0	1.56	11.6	24.7	FI	28
Exotic	5	17:24	18.0	51.0	1.60	13.0	4.2	FI	5
		Average	18.23	49.98	1.25	11.02	11.85		12.6
		Standard Error	0.07	0.24	0.15	0.41	2.54		2.5

4.3.3 Metal Sparks

Results for the metal sparks field experiments are summarised in Table 4.15. MC ranged from 9.2 to 13.0%. Throughout the experiments average ambient temperature and RH were 18.2ºC ± 0.1 s.e., and 50.0% ± 0.2 s.e. respectively. Ambient temperature was similar to the laboratory experiments (average of 21.8ºC), but average RH was much higher (50.0 vs. 34.4%). Average wind speed was 1.3 m/s ± 0.2 s.e.. Equation 4.1, with regression coefficients from the best model (Table 4.9), was used to calculate probability values for the field experimental observations.

All metal sparks samples ignited, as predicted by the probability of ignition success model. Each trial was predicted to have probability values from 0.86 to 0.89 (Table 4.16). Further discussion on this experiment is contained in Chapter Five.

Table 4.16 Probability predictions for the metal sparks field experimental observations using Equation 4.1, with regression coefficients from the best model (Table 4.8).

Grass Type	Trial	Predictor Variable	Probability (P(y=1))
		MC (%)	
Tussock	1	9.7	0.89
Tussock	2	10.9	0.88
Tussock	3	9.2	0.89
Tussock	4	10.0	0.89
Tussock	5	10.3	0.88
Exotic	1	11.3	0.88
Exotic	2	13.0	0.86
Exotic	3	11.2	0.88
Exotic	4	11.6	0.87
Exotic	5	13.0	0.86

4.3.4 Open Flame

Results for the open flame field experiments are summarised in Table 4.17. MC ranged from 10.2 to 19.3%. Throughout the experiments average ambient temperature, RH, and wind speed were 17.4ºC ± 0.1 s.e., 51.1% ± 0.1 s.e., and 0.9 m/s ± 0.1 s.e. respectively. Ambient temperature and wind speed were similar to the laboratory experiments (21.2ºC average, and 1 m/s), but average RH was much higher (51.1 vs. 31.8%). Equation 4.1, with regression coefficients from the best model (Table 4.10), was used to calculate probability values for the field experimental observations, with a wind speed of 1 m/s. All open flame samples ignited immediately, as predicted by the logistic regression model (Table 4.18). Further discussion on this experiment is contained in Chapter Five.

Table 4.17 Field experimental results for open flame.

Grass Type	Trial	Time	Ambient Temperature (°C)	RH (%)	Average Wind Speed at Experiment Level (m/s)	Average Moisture Content (%)	Ignition Type	Ignition Time (s)
Tussock	1	17:42	17.6	51.5	0.77	10.5	FI	0
Tussock	2	17:47	17.6	51.5	0.54	10.7	FI	0
Tussock	3	17:51	17.4	51.1	1.60	10.5	FI	0
Tussock	4	17:55	17.4	51.1	1.17	10.7	FI	0
Tussock	5	17:59	17.1	50.5	0.78	10.2	FI	0
Exotic	1	17:45	17.6	51.5	0.58	18.3	FI	0
Exotic	2	17:49	17.4	51.1	1.48	18.9	FI	0
Exotic	3	17:53	17.4	51.1	0.76	19.3	FI	0
Exotic	4	17:57	17.4	51.1	0.70	18.6	FI	0
Exotic	5	18:01	17.1	50.5	1.00	17.5	FI	0
		Average	17.40	51.10	0.94	14.52		
		Standard Error	0.06	0.12	0.12	1.34		

Table 4.18 Probability predictions for the open flame field experimental observations using Equation 4.1, with regression coefficients from the best model (Table 4.10).

Grass Type	Trial	Predictor Variables		Probability (P(y=1))
		Wind (1 m/s)	MC (%)	
Tussock	1	1	10.5	1
Tussock	2	1	10.7	1
Tussock	3	1	10.5	1
Tussock	4	1	10.7	1
Tussock	5	1	10.2	1
Exotic	1	1	18.3	1
Exotic	2	1	18.9	1
Exotic	3	1	19.3	1
Exotic	4	1	18.6	1
Exotic	5	1	17.5	1

4.4 Summary

Models were developed to predict probability of ignition success for all laboratory experiments except organic embers. Ignition thresholds were calculated by holding all variables constant except MC, or metal temperature in the case of hot metal, and solving for $P(y = 1) = 0.5$. Table 4.19 presents a summary of the ignition thresholds for each ignition source. The ignition threshold for the secondary carbon emissions model is not included because the model can only be used for a narrow range of ambient temperature and relative humidity. Furthermore, the ignition threshold was only slightly lower than for the preferred model (62% vs. 65% MC).

Table 4.19 Summary of ignition thresholds for each ignition source under different scenarios.

Ignition Source	Predictor Variable(s)	Scenario	Ignition Threshold
Hot Metal	MC (%), $wind_A$ (1 m/s), $wind_B$ (2 m/s), hot plate temperature (ºC), orientation (horizontal)	Vertical, Wind = 2 m/s, MC = 1%	398ºC
		Vertical, Wind = 1 m/s, MC = 1%	421ºC
		Horizontal, Wind = 2 m/s, MC = 1%	429ºC
		Horizontal, Wind = 1 m/s, MC = 1%	452ºC
Hot Carbon Emissions	MC (%)	N/A	65% MC
Metal Sparks	MC (%)	N/A	37% MC
Open Flame	MC (%), wind (1 m/s)	No wind	28% MC
		Wind = 1 m/s	55% MC

The ignition thresholds generated by the probability models were compared with observations gathered from field experiments. All models explained the field observations well except for carbon emissions. This was due to lower exhaust gas temperature in the field than was expected. The implications of these results are discussed in the following chapter.

The main null hypothesis from section 3.3 (Chapter Three) that there is no difference in the behaviour of cured grass samples between each of the five ignition sources and three wind speeds was rejected. This was justified by the difference in reported ignition thresholds for each ignition source and wind speed (hot metal and open flame outcomes only) (Table 4.19). However for each ignition source, there was no difference in the ignition behaviour between the two grass types. The secondary null hypothesis that there is no correlation between grass MC, time-to-ignition, and wind speed was not rejected.

Chapter 5. Discussion and Practical Applications

5.1 Introduction

This chapter considers and discusses the results for each of the five ignition sources in terms of previous work, model strength, and experimental design, and compares laboratory findings against those from the field experiments. Some recommendations for future research are also discussed, and are thoroughly presented in Chapter Six. Practical applications for the probability of ignition success models are suggested in terms of implications for use, and for decision-support tools for fire management.

5.2 Laboratory and Field Experiments

For each ignition source, several points were relevant. Models were applicable to both tussock and exotic grass types, since no significant difference in ignition behaviour was found between them. The ignition thresholds differed between ignition sources, as expected. A separate subsection (5.2.6) briefly discusses the lack of relationships found between time-to-ignition data and other variables. Model accuracy would likely improve by further investigation into the effect of higher wind speeds, and from an increased number of trials, especially for MC levels between 20 and 40%. Different grass sample types at various degrees of curing would also strengthen model predictive power and applicability.

5.2.1 Hot Metal

Some differences were found between the ignition threshold temperatures reported for this study and previous work. Regardless, hot metal ignition temperatures of dry (< 15% MC) grass fuels tested in a horizontal orientation, varied between 310 and 400ºC, as reported by several sources (Table 2.10). Knight and Hutchings (1987) was the only study found that involved vertically oriented grass samples, where an ignition temperature of 525ºC was reported for samples at a MC of 0%; but, this temperature seems high when compared with this and other studies. Literature also suggests that fuel orientation and length do have an effect on ignition temperature. These points are discussed in detail in the test that follows. Furthermore, there appears to be a slight difference in ignition behaviour between grass species used in this and previous studies.

The ignition threshold (398ºC for $P(y=1) = 0.5$) for the hot metal scenario involving vertical hot plate orientation, a MC of 1%, and wind speed of 2 m/s, was similar to studies conducted by Knight and Hutchings (1987), Rallis and Mangaya (2002), and Harrison (as cited by Babrauskas, 2003) where ignition of dry grass occurred at 400ºC for all three studies. The temperatures were reported for various wind speeds and MC values: 0% MC and 1.0 to

1.5 m/s (Knight & Hutchings, 1987), and dry MC (no specific value was reported) and 0.9 m/s (Harrison, as cited by Babrauskas, 2003). Rallis and Mangaya (2002) did not provide quantitative information, and reported samples as dry, and wind speed equal to blowing on the sample. Stockstad (1976) reported spontaneous ignition at a furnace temperature of 440ºC without wind, and MC values of ≤ 18%, which is comparable with predictions made by this model, but only for scenarios involving the horizontal hot plate orientation. Samples were cut into small lengths (< 4 cm), and were arranged horizontally for each of the previous studies. This sample arrangement likely facilitated ignition at wind speeds lower than 2 m/s, as it allowed more oxygen to flow through the sample (Babrauskas, 2003; Cheney & Sullivan, 2008).

The current study was conducted under similar environmental conditions and used a similar hot plate to Pitts (2007). Pitts (2007) varied wind speed to three levels (0, 1, and 2.5 m/s) and results suggested that increasing wind speed lowers the metal temperature required for grass-fuel ignition, which concurred with this study and is in accordance with Di Blasi *et al.* (1999). All ignition temperatures reported by Pitts (2007) were between 310 and 380ºC for a variety of live and dead grass samples at 10 to 14% MC. These lower ignition temperatures could be attributed to sample length and the horizontal orientation of the copper hot plate — samples were cut up and arranged in a wire cage 2.5 cm deep, and placed on top of the hot plate for testing. This would have caused heat to rise up into the samples, with a generous flow of oxygen (Babrauskas, 2003). Higher metal temperatures may have been required for this study due to the downward-facing (horizontal), and side-facing (vertical) hot plate orientations, longer grass lengths and denser samples, which prevented steady oxygen flows through the sample. Furthermore, heat transfer is predominantly upwards (Babrauskas, 2003), as opposed to downwards or horizontally; therefore, less heat would have been directed into samples in this study compared with Pitts (2007). It would be useful to repeat the study by Pitts (2007) with different hot plate orientations. For example, it could be placed on top of the cut up samples or vertically next to a pile of samples. Results from the current study suggest that 100% cured grass, in its natural vertical orientation, has higher ignition threshold temperatures than does grass in the horizontal orientations used by Pitts (2007).

Ignition thresholds were reported to be much lower than two previous studies: Fairbank and Bainer (as cited by Babrauskas, 2003), who reported 663ºC as the ignition temperature of dry grass, and Knight and Hutchings (1987), who reported 525ºC as the ignition temperature of dry grass under the following conditions: vertical orientation, 0% MC, and 1.0 to 1.5 m/s wind speed. The original study by Fairbank and Bainer could not be obtained, and little detail was included in the citation by Babrauskas (2003); however, the reported ignition temperature seems unusually high. Knight and Hutchings (1987) found that grass fuel ignition was dependent on arrangement, as reported by several others (e.g., Chandler *et al.*, 1983; Pyne *et al.*, 1996; Tolhurst & Cheney, 1999; Cheney & Sullivan, 2008) (refer to Chapter Two). Slight variations in sample arrangement can produce contradictory results. The force of contact between the vertical samples and the hot metal was not indicated by this study nor that of Knight and Hutchings (1987). Samples in this study were pushed into the hot plate (vertical), or pushed down by the hot plate (horizontal). If force of contact between samples and the hot plate was higher in this study compared with Knight and Hutchings (1987), it may justify the lower ignition temperatures reported.

It would be beneficial to increase exposure time between the hot plate and grass samples from five to ten minutes, to simulate longer vehicle idling times. Kaminski (1974) used an exposure time of ten minutes and reported ignition temperatures of 330ºC, comparable with Pitts (2007). In most cases, exposure time was the same for this study and Pitts (2007), but in some cases Pitts (2007) used a longer exposure time, which may also explain the lower ignition temperatures reported. Ignition temperatures for this study may decrease with a longer exposure time; although in reality, the likelihood that a vehicle would remain idling for up to ten minutes or longer is low. Thus, results from this recommendation may not be relevant for practical application.

For this model, the four different scenarios described in Chapter Four (Table 4.5) explained ignition behaviour well. The probability curves, based on hot plate temperature and the four scenarios, all followed the same sigmoidal shape (Figure 4.3). The curve was neither very steep, nor very flat, indicating that the model was neither very strong, nor very weak. The predictor variables' strength of association values also reflect this (Table 4.4). Ignition temperature was predicted to increase slowly as MC increased. This implies that MC did not have a very strong effect on ignition probability, which was probably due to the exposure time of five minutes that allowed fuels to preheat to their ignition point. With sufficient exposure time at a given hot metal temperature, grass may ignite at MC levels over 100% (Table 5.1).

Table 5.1 Summary of hot metal laboratory experimental results.

Hot Plate Orientation	Wind Speed (m/s)	Number of Successful Ignitions	Percentage of Samples that Successfully Ignited for the given Wind Speed (%)	Ignition Temperatures (ºC)	MC Range (%)
Vertical	2	13	24	390 to 395	1 to 21, but one sample ignited at 76
Vertical	1	22	39	above 421	0.6 to 111
Vertical	0	4	7	493	below 13
Horizontal	2	~	0	~	~
Horizontal	1	6	17	418 to 445	below 5
Horizontal	0	~	0	~	~

For the vertical orientations, the model predicted an ignition threshold (P(y=0) = 0.5) of 398ºC, for a wind speed of 2 m/s, and MC of 1%. Actual results indicated that flaming ignition occurred at hot plate temperatures as low as 390ºC, and MC levels up to 76% (Table 5.1). When wind speed was set to 1 m/s, the ignition threshold was 421ºC at MC of 1%, and actual results concurred with this. Samples ignited at MC values up to 111%. At wind speed of 0 m/s, the model predicted no ignitions for any of the hot plate temperatures tested. However, four ignitions did occur at 493ºC, all with MC values lower than 13%.

For the horizontal orientations the model predicted an ignition threshold of 429ºC, for a wind speed of 2 m/s and MC of 1%. However, actual results indicated that no ignitions occurred at all (Table 5.1). There are four possible explanations for this:

1) the horizontal hot plate orientation facilitated heat transfer on the top side of the hot plate (away from the fuels) rather than the bottom side (toward the fuels), with hot air convection rising up from the hot plate rather than projecting down towards the sample;
2) the wind cooled air that was projected downwards onto the sample;
3) only the tops of the grass samples were in contact with the hot plate, and this level of contact may not have been sufficient for ignition;
4) the downward-facing hot plate created a stratified environment, which prevented the fuel and oxygen from readily mixing (Babrauskas, 2003).

The model predicted the probability of ignition (P(y=1) = 0.5) of 452ºC with a wind speed of 1 m/s, and MC of 1%; but, actual results indicated that flaming ignition occurred at temperatures as low as 418ºC, for MC values below 5%. This is closer to the ignition probability prediction for vertical hot plate orientation. When wind speed was 0 m/s, the model predicted that ignition would not occur at any of the hot plate temperatures tested, as found in the laboratory experiments. Discrepancies between predicted and actual results can be attributed to model weaknesses, and limitations in the experimental design and data set, as described below.

The metal threshold temperatures were reported for conditions involving grass at MC values of 1%. In the field, MC will likely never be this low, with the lowest MC values at about 3% (Pyne *et al.*, 1996). Therefore, the metal temperatures should be considered conservative estimates, but do have some error associated with predictions as previously mentioned.

A wider range of hot plate temperatures should be tested at different wind speeds and hot plate orientations. Hot plate use was limited, as it could not be set to temperatures higher than 500ºC. In addition, wind cooled the hot plate, limiting the hot plate temperature levels for trials in the presence of wind.

Variations in ignition success at different MC levels can be ascribed to subtle differences in sample arrangement. Every effort was made to ensure sample consistency, but some samples made contact with the hot plate such that ignition either occurred when it was unexpected, or did not occur when expected. Natural variability of grass fuels, such as different cell structure or size, blade length, presence of inflorescence, or hardiness, may have contributed to this. This variability depended on the fuel's exposure to different environmental conditions during growth, such as climate and microsite as described in Cheney and Sullivan (2008). Furthermore, the reported MC levels represented average MC of the entire sample; yet, individual blades would have varied in MC depending on cell structure. Ignition success at higher MC levels may have been caused by initial hot metal contact with a portion of the sample at a lower MC than the rest of the sample, allowing it to preheat to the ignition point, and enabling adjacent fuels to successfully ignite.

There was a lack of samples that were conditioned to MC values between 20 and 50%, and this was not discovered until the analysis phase of the project. This probably occurred because several samples initially ignited at MC values above 50%. Therefore, the trial-and-error method (used to condition the samples to higher MC values) warranted the preparation of samples with higher MC values. All MC values for the horizontal orientation were below 7%, because there were only six flaming ignitions for all samples (n = 108) tested for that orientation.

Results from field experiments were correctly predicted by the model. They indicated that ATVs may pose a higher ignition risk compared with unloaded, maintained utility vehicles. Both the exhaust system temperatures of the Nissan Navara 2006 and the ATV were comparable with previous studies (Baxter, 2004; Gonzales, 2008; Palmu & Baxter, 2008).

Further field tests to investigate the ignitibility of grass samples *in situ*, under varying environmental conditions would be useful. Testing a diverse range of vehicles would increase the knowledge of ignition risk from different vehicle types.

5.2.2 Hot Carbon Emissions

The literature indicated that this experimental design had not been previously tested, with only two studies found to be comparable with the results. Nevertheless, several sources provided useful information for the experimental design (San Dimas EDC, 1980; Davis *et al.*, 1999; Heisler, 1999; DeHaan, 2002; Babrauskas, 2003; Gonzales, 2003a; 2003b; Bosch, 2004; Gonzales, 2008). Maxwell and Mohler (1973), and San Dimas EDC (1980) reported that grass fuel ignitions were possible with hot carbon particles as small as 1.5 and 2.3 mm respectively. This study has expanded on these conclusions to report that particles as small as 1.0 mm can ignite dead grass fuels. However, this result is only valid if the sparks are accompanied by an air flow of 3.7 m/s at 200ºC.

Of the two significant models reported, neither included grass type as a predictor variable; although, it was slightly significant. There are two main reasons to warrant exclusion of grass type from the model. Firstly, the models were simpler without specifying grass type, and their exclusion did not greatly affect model accuracy. This also allows for easier operational application of the models in the field. Secondly, glowing carbon particles seemed to land in exotic grasses and remain in place much more readily than in tussock grasses. Tussock grass blades are much smoother than those in exotic grasses, and it was observed that significantly fewer glowing carbon particles remained on these tussock grasses during experiments. This was probably related to the roughness properties of the grass types and the carbon particles (Maxwell & Mohler, 1973; DeHaan, 2002; Babrauskas, 2003) (Chapter Two). Visual observations confirmed that if glowing carbon particles landed on the sample and remained there, it was likely that the sample would ignite. Therefore, the difference in ignitibility was attributed to the probability of the hot carbon particles landing and remaining on the sample. Only 30% of the exotic grass samples did not ignite, compared with 63% of the tussock samples.

Although the two reported models were significant, the sigmoidal curves were quite flat (Figures 4.4 and 4.5). This indicated that the models were weak and that there was high variability in the reported ignition thresholds. The predictor variables' strength of association values also reflect this (Table 4.7). Results indicated that there was high variability in MC levels of the samples that successfully ignited. This can be attributed to the five minute exposure time that allowed samples to preheat to their ignition point, and may have contributed to model weakness. With an exhaust gas temperature of 200ºC, ignition occurred at MC values up to 116% (Table 5.2); however, field experiments suggested that the exhaust gas temperature of some vehicles did not remain that high when idling (Chapter Four).

Table 5.2 Summary of the hot carbon emissions laboratory experimental results.

Number of Successful Ignitions	Percentage of Successful Ignitions (%)	MC Range (%)
29	54	0.5 to 116

The exhaust gas of the Nissan Navara 2006 did not exceed 115ºC during the field experiments. This may have occurred because the engine was idling for over five minutes while the hot metal experiments were conducted, which may have caused the exhaust gas temperature to drop. Literature suggested that 200ºC is representative of hot exhaust gas temperatures (Maxwell & Mohler, 1973; Heisler, 1999; Bosch, 2004; Gonzales, 2008); however, exhaust gas temperatures do vary between vehicles, and cool when the engine is idling (see Figure 3.8 for an example of rate of cooling).

This experimental design was strong, and facilitated repeatability; therefore, a larger data set, with increased repetition would be useful to better understand the risks from of this ignition source.

5.2.3 Metal Sparks

Babrauskas (2003) and DeHaan (2002) investigated ignition from metal sparks in fuels that were similar to grasses, reporting that metal sparks are a significant ignition source and have been found to ignite sawdust and wood shavings.

Surprisingly, results suggested that metal sparks can ignite grass at MC values of up to 69% (Table 5.3), with 13 successful ignitions occurring for samples containing over 35% MC. The results differ from Cheney and Sullivan (2008), who state that grass fuels can only ignite from metal sparks if dead fuel MC is less than 6%, and that only a persistent flame can cause ignition if dead fuel MC is over 15%. However, they do not indicate the environmental conditions required to support these ignition thresholds. The current study showed that 55% of successful ignitions occurred at dead fuel MC levels above 6%, where flaming occurred after less than 30 seconds of grinding steel with an average sized grinder.

Table 5.3 Summary of metal sparks laboratory experimental results.

Number of Successful Ignitions	Percentage of Successful Ignitions (%)	MC Range (%)
85	52	1 to 69

The probability of ignition success model fitted the experimental data well (subsection 4.2.4). Visual observation indicated that during each trial some of the metal sparks did not come into contact with the samples, but it was impossible to quantify this. In some cases, the grinder slipped off the steel for a second, which probably allowed the sample to cool down enough to delay or prevent ignition. This was probably the case for ten samples that contained less than 37% MC, but did not ignite. This explains the weak form of sigmoidal curve at the low MC end of the graph (Figure 4.5). In addition, six samples that contained more than 37% MC ignited. These samples may have been subjected to a concentrated stream of sparks, allowing them to preheat sufficiently to support ignition. Variability in the stream of sparks would also occur in field conditions. Notwithstanding this, the model remains highly significant, and is applicable for determining ignition risk from variable use of grinders in the field.

Samples were conditioned to a wide variety of MC levels, but more at samples at MC levels between 20 and 50% would have been beneficial. There were no samples conditioned to the MC class of 23.00 to 29.99%. This was due to the trial-and-error method of conditioning samples.

5.2.4 Organic Embers

Organic embers were difficult to simulate in the laboratory. The lack of ignitions was most likely due to the ratio of grass to soil being too low, which prevented the disks from smouldering and retaining heat (Babrauskas, 2003). But, if the disks had contained less soil, they probably would not have held their shape. As soon as the disks were removed from the hot plate they began to lose heat. In retrospect, it would have been useful to measure the disk temperature loss over time. Results indicated that disk temperature loss was probably quite rapid; otherwise ignitions could have occurred at initial organic ember temperatures, as they approximated those which were used for the hot metal experiments.

Only one study was found that has investigated this ignition source (Baxter, 2004), but it did not investigate the ignitibility of grassland fuels. It reported that ATVs were capable of igniting vegetation that had accumulated on the exhaust system, and that this vegetation remained smouldering when it fell off the ATV. There is still a low understanding of this ignition source and its effect on ignitibility of grassland fuels. It would be useful to combine experimental methods from this and Baxter (2004)'s study for future investigation.

5.2.5 Open Flame

None of the previous studies reviewed in Chapter Two can be directly compared with the ignition thresholds reported for the open flame experiment, as experimental methodologies varied. Dimitrakopoulos *et al.* (2010) conducted field tests on vertically oriented grass and determined an ignition threshold of 38% MC, but the degree of curing varied from 0 to 100%, and ambient temperature, RH, and wind speed ranges were higher (Table 2.5). The threshold was based on fuel MC only, but observations indicated that wind speeds of up to 4 m/s were required to ignite fuel with MC values between 30 and 42%. This observation is related to results from this study, where without wind thresholds were reported at a MC of 28%, and with wind thresholds were higher (55% MC). Dimitrakopoulos *et al.* (2010) recorded successful ignition if a flame was sustained for at least one minute. This criterion differed to this study, which recorded successful ignition if a flame was present after 20 seconds, and the sample had completely burned 30 seconds after that (Table 4.1). This may explain why their study reported that no ignitions occurred for samples with more than 42% MC.

Blackmarr (1972) and de Groot *et al.* (2005) used flaming matches as open flame ignition sources, and reported various ignition thresholds for different scenarios (Table 2.5). Neither study investigated the effect of wind presence. Blackmarr (1972) reported that small flaming matches ignited slash pine litter at MC values up to 25%. This is similar to the ignition threshold of 28% MC without wind determined in this study; however, the litter in Blackmarr's (1972) study was arranged horizontally and consisted of smaller fuel lengths. The ignition threshold for dead grass, reported by de Groot *et al.* (2005), was higher than for this study (35 vs. 28% MC); but again, samples were horizontally arranged. These observations suggest that horizontally oriented dead grass may ignite more readily at higher MC levels compared to vertically oriented dead grass, which is due to the buoyancy of the convective heat plume in relation to fuel orientation (Babrauskas, 2003). This was also inferred from comparisons with the work carried out for hot metal ignition sources (subsection 5.2.1).

The open flame used in this study was located adjacent to the grass sample, not above or below it. Grass fuel ignited more readily and at higher MC levels when subjected to a light wind speed of 1 m/s. This agrees with a previous study where the ignitibility of litter from Australian shrubs and trees was found to be affected by wind and the location of the open flame ignition source (Plucinski & Anderson, 2008) (Chapter Two). It also concurs with

Marsden-Smedley *et al.* (2001), who reported that with increasing wind speed, there is more probability of sustaining fire at higher MC levels. Without wind, ignitions for this study occurred at lower MC levels than for gorse (Anderson & Anderson, 2010), but with light wind (1 m/s) ignitions occurred at higher MC levels. Furthermore the ignitibility of grassland fuels is higher than reported thresholds for radiata pine litter (<20%) (Woodman & Rawson, 1982), which suggests that fire ignitions in grasslands can occur at higher FFMC levels than for radiata pine litter.

The probability of ignition model was highly significant, and was the strongest model of all ignition sources examined in this study. The sigmoidal curve was very steep, approaching both one and zero closely. The change in probability levels from 0.9 to 0.1 occurred over small MC ranges: without wind - 20 to 35%, comparable with previous studies (Blackmarr, 1972; de Groot *et al.*, 2005), and with a wind speed of 1 m/s - 48 to 63%. As reported in Chapter Four, the model predicted ignition successes and failures with a high degree of accuracy (97%). Table 5.4 presents a summary of the ignition successes for each wind speed tested. No samples ignited above the reported threshold at a wind speed of 1 m/s, but without wind two samples ignited at a MC value slightly over the reported threshold.

The model was not significant at a wind speed of 2 m/s. This was largely due to the strength of the open flame. Wind speeds of 2 m/s often blew the flame out. Each time this occurred it was immediately relit, but this caused inconsistency in the results, and explains the non-significance of the model with wind at 2 m/s. Interestingly, results at the wind speed of 2 m/s approximate those recorded with wind speed at 0 m/s, where successful ignitions occurred up to MC values of 38% (Table 5.4). All ignitions occurred for samples with MC values below 26%, except for one observation at 38% MC. Furthermore, four samples between 30 and 38% MC did not ignite. These observations indicate that with a wind speed of 2 m/s, an ordinary lighter is unlikely to ignite dead grass fuels at MC levels higher 28%, even if the flame has been blown out and repeatedly lit within 20 seconds; however, wind variability in the field at fuel level should be considered when making management decisions.

Table 5.4 Summary of actual open flame laboratory experimental results.

Wind Speed (m/s)	Number of Successful Ignitions	Percentage of Successful Ignitions (%)	MC Range (%)
0	19	35	below 32
1	25	52	below 54
2	18	46	below 38

5.2.6 Discussion of Linear Regression

As Chapter Four reports (Figure 4.1 and Table 4.2), none of the relationships between time-to-ignition and MC or hot metal temperature were significant. This is surprising, as one would expect time-to-ignition to increase as MC increases (e.g., Xanthopoulos & Wakimoto, 1993; Dimitrakopoulos & Papaioannou, 2001; Dimitrakopoulos *et al.*, 2006), and time-to-ignition to decrease as hot metal temperature decreases (e.g., Di Blasi *et al.*, 1999; Pitts, 2007). However, Curt *et al.* (2007) reported that time-to-ignition could not be predicted, which is in accordance with this study. The non-significance of hot metal temperature and time-to-ignition was probably related to the variability in sample MC, which was not considered in the analysis. When analysed with wind speed, the low significance found for hot metal time-to-ignition data was probably related to the five minute exposure time, which was long enough for a pattern in the data to develop (Babrauskas, 2003). Sample size may not have been normal nor large enough, with little samples conditioned to MC values between 20 and 40% (Crawley, 2007). Another reason for the lack of significance can be attributed to subtle differences in sample fuel and arrangement, as discussed in subsection 5.2.1 (Chandler *et al.*, 1983; Pyne *et al.*, 1996; Cheney & Sullivan, 2008).

5.3 Practical Applications

For all ignition sources tested, the models are only fully reliable if applied under the same range of conditions that were present in the laboratory (Table 3.3). They should be used with caution if applied to conditions outside of the experimental data range: for example, wind speeds higher than 2 m/s, RH values less than 27% or above 54%, and ambient temperatures less than 17ºC or above 26ºC. It is likely that with lower RH values and higher ambient temperatures, ignition probabilities could be under-predicted by the models. If the ignition probability is predicted for grass samples that are less than 100% cured, it is more likely that ignition probability will be over-predicted. Users can apply these models to conditions beyond those specified, but should be aware of the models' limitations and cautions, particularly with the weaker models.

5.3.1 Guidelines and Implications

5.3.1.1 Hot Metal

A range of different scenarios can be selected for this model depending on the orientation of grass contact with hot metal surfaces, wind speed, and MC value. The worst-case scenario was chosen to represent situations where grass fuels are extremely dry (about 3% in the field). This was reported for a MC of 1%, a wind speed of 2 m/s, and a vertical hot plate orientation (Chapter Four). Fire managers should use this scenario if grass fuels are assumed to have full contact (including the side and tops of grass blades) with hot metal parts for five minutes or less. The model (Equation 4.1, with regression coefficients from Table 4.3) can be used for wind speeds greater than 2 m/s; however, ignition may occur at lower metal temperatures than the model predicts. Inputs required for this scenario include fuel MC, hot metal temperature, and $wind_B$ (2m/s), where $wind_B$ is set to one, and the other predictor variables ($wind_A$ and orientation) are set to zero. For the same orientation, but a wind speed of 1 m/s, the same inputs are required, but $wind_A$ is set to one and $wind_B$ is set to zero.

The scenarios involving a horizontal hot plate orientation, with wind speeds of 2 and 1 m/s should be applied if contact is between the tops of grass blades and the ground-facing hot metal parts. These scenarios assume that contact is lower than for the vertical hot plate scenarios, and is for five minutes or less. Inputs required for this scenario include the fuel MC, hot metal temperature, $wind_B$ (2 m/s), and orientation (horizontal), where $wind_B$ is set to one, orientation is set to one, and $wind_A$ is set to zero. For the same orientation, but a wind speed of 1 m/s, the same inputs are required, but $wind_A$ is set to one and $wind_B$ is set to zero.

Even at the highest hot plate temperature used for trials (493ºC), the model predicted a very low probability of ignition (≤ 0.23) when applied to situations with no wind. Further work is required to confidently predict the probability of ignition under these conditions.

5.3.1.2 Carbon Emissions

The model containing only MC as a predictor variable is recommended for application under most environmental conditions, but with caution (Scenario 2). The model requiring MC, ambient temperature, and RH, should only be applied under a limited range of ambient temperature and RH (Scenario 1) (subsection 5.3.2.2).

For scenario one, the inputs include MC, ambient temperature, and RH, using Equation 4.1, with regression coefficients from Table 4.6 (Secondary Model). Unless the ambient temperature and RH are the same as the averages reported in Figure 4.5 (19.4ºC and 41.1%), the probability of ignition values will differ from the displayed curve. If ambient temperature is higher, and RH is lower, a higher probability of ignition for a given MC level is predicted compared with the MC only model. The opposite occurs if ambient temperature is lower and RH is higher. Ignitibility prediction for scenario two is simple: input the MC level of the cured grass into Equation 4.1, with regression coefficients from Table 4.6 (Preferred Model), to calculate the probability of ignition.

5.3.1.3 Metal Sparks

The ignition thresholds model for metal sparks requires only a MC value for fully cured grass to calculate the probability of ignition using Equation 4.1 and regression coefficients from Table 4.9.

5.3.1.4 Open Flame

The model for open flame ignition sources can be applied to situations with no wind, or light wind (1m/s). If wind is 2 m/s, and the model is being used to predict ignition probability from an ordinary lighter, users should input variables for the situation with no wind, and apply the outputs with caution. If the model is being used for predictions from a resilient flame (such as a gas cooker) with wind speeds above 1 m/s, users should input variables for the situation with light wind (1 m/s), as the laboratory conditions resulted in the pilot flame being extinguished at wind speeds of 2 m/s, making the model unreliable at this wind speed.

To use the model (Equation 4.1 with regression coefficients from Table 4.10) for situations with no wind, wind is set to zero, and the desired MC value is used to calculate the probability of ignition. For situations with light wind (1 m/s), or wind above 2 m/s, wind is set to one, and the desired MC value is used to calculate the probability of ignition.

5.3.2 Decision-Support Tools

Examples of decision-support tools have been developed using the logistic regression models for the four ignition sources. If it is assumed that fire managers consider an ignition probability of 0.7 to be a critical threshold for risk management purposes (Teeling, personal communication, February 4, 2010), then the conditions under which this ignition probability will be reached can be determined for each of the four ignition sources. Consequently, relationships between predictor variables were calculated and are presented for hot metal and open flame ignition sources, at a 70% probability of ignition. For carbon emissions and metal sparks, the MC levels corresponding to a 70% probability of ignition are reported. Fuel MC values were also converted into the corresponding FFMC values from the FWI System using the equation (5.1) by Van Wagner (1987):

Equation 5.1

$$MC = \frac{147.2 \times (101 - FFMC)}{59.5 + FFMC}$$

since the FFMC is commonly used and understood by New Zealand fire managers (Table 5.5). The thresholds were calculated as a guide only, and do not imply that ignitions will not occur above the reported values. Several other decision-support tables were created, and include a range of probability values for different MC levels and other predictor variables. They were highlighted with different colours to show different probability ranges (Table 5.6).

Table 5.5 MC and the corresponding FFMC values from the FWI (Van Wagner, 1987).

MC (%)	1	5	10	15	20	25	30	35	40	45	50	55	60
FFMC	100	96	91	86	82	63	74	70	67	63	60	57	55

Table 5.6 Probability ranges associated with the colours on the decision-support tables.

Colour	**Probability Range**
Green	0 to 0.49
Yellow	0.50 to 0.70
Orange	0.71 to 0.80
Red	0.81 to 100

5.3.2.1 Hot Metal

The hot metal probability of ignition model can be used to predict metal ignition threshold temperatures, based on the variables that were used for the experiments. In reality, fire managers probably will not be familiar with the exhaust system temperatures of various vehicles. For the environmental conditions present during the field experiments, average metal temperatures for the hottest part of exhaust systems from the maintained Nissan Navara 2006, and the Honda Foreman ATV, while they were idling, were 218 and 469ºC respectively (Table 4.12, Chapter Four). Other studies reported exhaust system temperatures of similar vehicles during operation. Gonzales (2008) reported metal temperatures of up to 375ºC for maintained diesel utility vehicles, which was similar to the maximum temperature (393ºC) recorded in the tests conducted for this study (Figure 3.8, Chapter Three). However, these metal temperatures do cool when in idle, and were lower than the threshold outcomes of this study. Both Baxter (2004) and Palmu and Baxter (2008) reported metal temperatures of operating ATVs that were similar to those reported for the idling ATV in this study (Table 2.1, Chapter Two). These observations suggest that the exhaust systems of ATVs do not cool as rapidly as those of diesel utility vehicles. Furthermore, the recorded exhaust system temperatures of ATVs were within the thresholds predicted by the hot metal probability of ignition model.

The maximum exhaust system temperature recorded in this study was 512ºC at the manifold of the idling ATV (Table 4.12. Chapter Four).This temperature is higher than the maximum temperature used to develop the model; therefore, managers should assume that all temperatures predicted by the model can be reached by ATVs while operating or idling in the field. According to the results of this study, managers should assume that maintained diesel utility vehicles pose little ignition risk to grassland fuels, as their exhaust system temperatures will probably rarely reach ignition threshold temperatures.

Based on the logistic regression model, four graphs were produced to represent different relationships between MC and hot metal temperature for an ignition probability of 70% (Figure 5.1). For each scenario, the equation representing the relationship between the two variables is displayed. The equations can be used to calculate the hot metal temperature corresponding to a 70% probability of ignition at the given MC level. Selected MC values and the related FFMC values are displayed in Table 5.7.

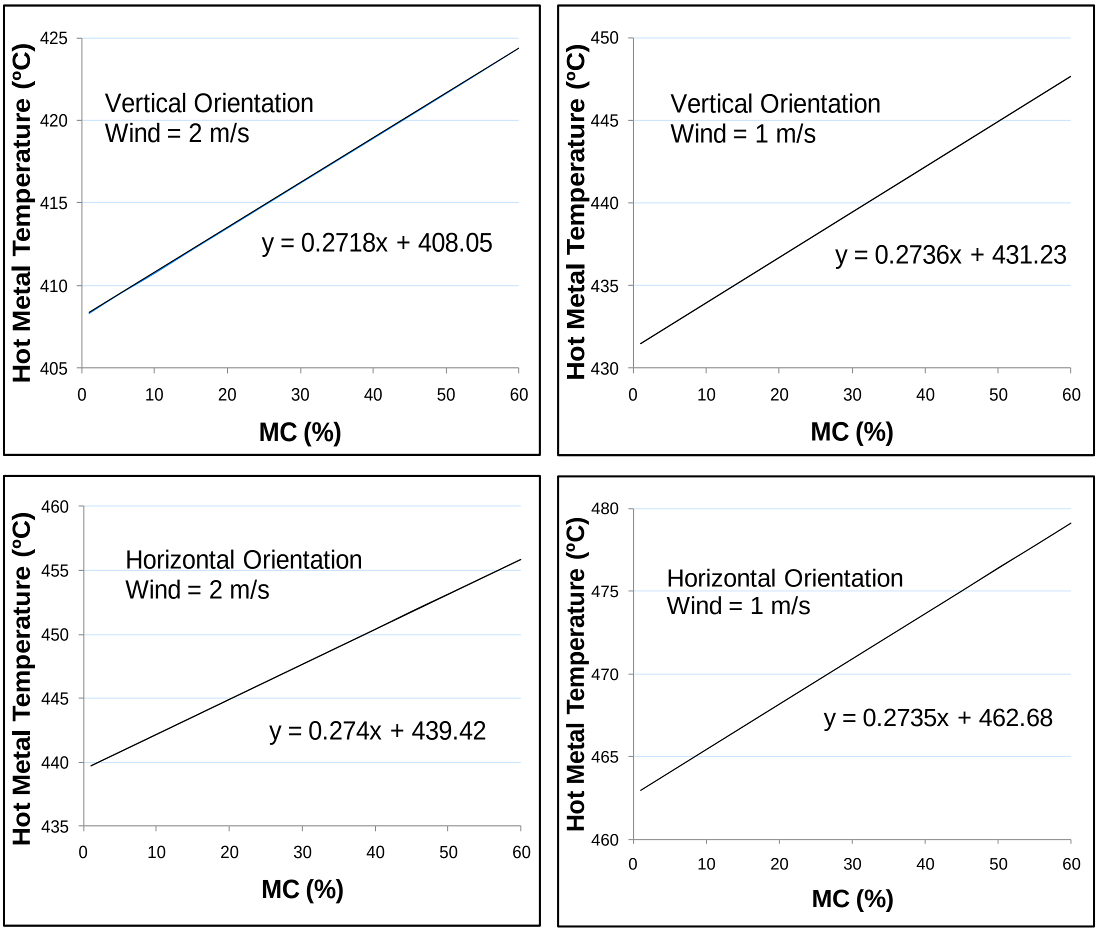

Figure 5.1 Relationships between hot metal predictor variables for an ignition probability of 70% under four different scenarios.

Table 5.7 Decision-support table with MC and FFMC values for a 70% probability of ignition from hot metal.

Ignition Thresholds for Management Applications (P(y=1) = 0.70)					
Scenario	MC = 1%	MC = 10%	MC = 20%	MC = 40%	MC = 60%
	FFMC = 100	FFMC = 91	FFMC = 82	FFMC = 67	FFMC = 55
Vertical Orientation - Full contact between grass fuels and hot metal Wind speed = 2 m/s	408ºC	411ºC	413ºC	419ºC	424ºC
Vertical Orientation - Full contact between grass fuels and hot metal Wind speed = 1 m/s	432ºC	434ºC	437ºC	442ºC	448ºC
Horizontal Orientation - Contact between the tops of grass fuels and hot metal Wind speed = 2 m/s	440ºC	442ºC	445ºC	450ºC	456ºC
Horizontal Orientation - Contact between the tops of grass fuels and hot metal Wind speed = 1 m/s	463ºC	465ºC	468ºC	474ºC	479ºC

Decision-support tables were developed for each of these four scenarios, listing probability values for several different combinations of MC and hot metal temperature. Table 5.8 represents full contact (vertical orientation), and Table 5.9 represents contact with grass tops only (horizontal orientation). The tables provide a quick and easy reference to aid management decisions. The ignition probabilities increase significantly (> 70%) when metal temperatures are between 405 and 465°C, depending on the scenario.

This approach was repeated for each of the three remaining ignition sources in the sections that follow.

Table 5.8 Decision-support table of ignition probabilities for full contact of dead grass fuel with hot vehicle parts, depending on hot metal temperature, fuel MC, and wind speed (vertical hot plate orientation).

Wind Speed = 2 m/s (Scenario with highest ignition risk - Full contact with grass fuels)		**MC (%)**												
		1	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
Temperature (ºC)	**365**	0.06	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
	375	0.13	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.06	0.05	0.05	0.04	0.04
	385	0.26	0.24	0.22	0.20	0.19	0.17	0.16	0.14	0.13	0.12	0.11	0.10	0.09
	395	0.44	0.42	0.39	0.37	0.34	0.32	0.29	0.27	0.25	0.23	0.21	0.19	0.18
	405	0.64	0.62	0.59	0.57	0.54	0.51	0.48	0.46	0.43	0.40	0.37	0.35	0.32
	415	0.80	0.79	0.77	0.75	0.73	0.70	0.68	0.65	0.63	0.60	0.58	0.55	0.52
	425	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79	0.77	0.75	0.73	0.71
	435	0.95	0.95	0.94	0.94	0.93	0.92	0.92	0.91	0.90	0.89	0.87	0.86	0.85
	445	0.98	0.98	0.97	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.94	0.93	0.93
	455	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97
	465	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98
	475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
	485	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	495	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Wind Speed = 1 m/s (Full contact with grass fuels)		**MC (%)**												
		1	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
Temperature (ºC)	**365**	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	375	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	385	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01
	395	0.11	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03
	405	0.21	0.20	0.18	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.08	0.07	0.07
	415	0.38	0.36	0.33	0.31	0.28	0.26	0.24	0.22	0.20	0.19	0.17	0.15	0.14
	425	0.58	0.56	0.53	0.50	0.47	0.45	0.42	0.39	0.37	0.34	0.32	0.29	0.27
	435	0.76	0.74	0.72	0.69	0.67	0.64	0.62	0.59	0.57	0.54	0.51	0.48	0.45
	445	0.87	0.86	0.85	0.84	0.82	0.80	0.79	0.77	0.75	0.72	0.70	0.68	0.65
	455	0.94	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81
	465	0.97	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.92	0.91	0.91
	475	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.96	0.96	0.96
	485	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98
	495	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99

Table 5.9 Decision-support table of ignition probabilities for contact of the tops of dead grass fuels with hot vehicle parts, depending on hot metal temperature, fuel MC, and wind speed (horizontal hot plate orientation).

Wind Speed = 2 m/s (Contact with the tops of grass fuels)	**MC (%)**												
Temperature (ºC)	**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
365	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
375	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
385	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
395	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
405	0.12	0.11	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.04
415	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.13	0.12	0.10	0.09	0.09	0.08
425	0.41	0.39	0.37	0.34	0.32	0.29	0.27	0.25	0.23	0.21	0.19	0.17	0.16
435	0.61	0.59	0.57	0.54	0.51	0.48	0.45	0.43	0.40	0.37	0.35	0.32	0.30
445	0.78	0.77	0.75	0.72	0.70	0.68	0.65	0.63	0.60	0.57	0.55	0.52	0.49
455	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79	0.77	0.75	0.73	0.71	0.69
465	0.95	0.94	0.94	0.93	0.92	0.91	0.91	0.90	0.88	0.87	0.86	0.85	0.83
475	0.98	0.97	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.94	0.93	0.93	0.92
485	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.96
495	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98

Wind Speed = 1 m/s (Contact with the tops of grass fuels)	**MC (%)**												
Temperature (ºC)	**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
365	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
375	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
385	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
395	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
405	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
415	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01
425	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03
435	0.19	0.18	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.08	0.07	0.07	0.06
445	0.35	0.33	0.31	0.28	0.26	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.13
455	0.55	0.53	0.50	0.47	0.44	0.42	0.39	0.36	0.34	0.31	0.29	0.27	0.25
465	0.73	0.72	0.69	0.67	0.64	0.62	0.59	0.56	0.54	0.51	0.48	0.45	0.43
475	0.86	0.85	0.84	0.82	0.80	0.78	0.77	0.74	0.72	0.70	0.68	0.65	0.63
485	0.93	0.93	0.92	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79
495	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.92	0.91	0.91	0.90

5.3.2.2 Carbon Emissions

The MC and corresponding FFMC values were determined for an ignition probability of 70% (Table 5.10). Scenario one represents the secondary model (with average ambient temperature of 19.4ºC and RH of 41.1%), which was more statistically significant than the preferred model. However, scenario two represents the preferred model, which was preferred because it is more suitable for application under a wider range of environmental conditions. Table 5.11 presents several probability of ignition values for various MC levels and is colour coded as previously described.

Table 5.10 Decision-support table with MC and FFMC values for a 70% ignition probability from carbon emissions.

	Ignition Thresholds for Management Applications (P(y=1) = 0.70)	
	MC (%)	**FFMC**
Scenario 1 Ambient temperature between 18.5 and 20.1ºC AND RH between 31 and 54%	37	69
Scenario 2 Other environmental conditions - use with caution	19	83

Table 5.11 Decision-support table of ignition probabilities for grass fuels from hot carbon emissions from vehicle exhausts, depending on MC, ambient temperature, and RH.

IS THE AMBIENT TEMPERATURE BETWEEN 18.5ºC AND 20.1ºC **AND** IS THE RELATIVE HUMIDITY BETWEEN 31% AND 54%?

YES Scenario 1 — **NO** Scenario 2

MC (%)	Scenario 1	Scenario 2
1	0.89	0.76
5	0.87	0.75
10	0.85	0.73
15	0.83	0.71
20	0.81	0.69
25	0.78	0.67
30	0.75	0.65
35	0.72	0.63
40	0.68	0.61
45	0.64	0.59
50	0.60	0.57
55	0.56	0.54
60	0.52	0.52
65	0.48	0.50
70	0.43	0.48
75	0.39	0.45

5.3.2.3 Metal Sparks

The MC and FFMC values for a 70% probability of ignition are 26% and 77 respectively. Table 5.12 presents several probability of ignition values for various MC values.

Table 5.12 Decision-support table of ignition probabilities for grass fuels from metal sparks, depending on MC.

		Probability of Ignition
MC (%)	1	0.94
	5	0.92
	10	0.89
	15	0.84
	20	0.78
	25	0.71
	30	0.63
	35	0.54
	40	0.44
	45	0.35
	50	0.27
	55	0.20
	60	0.15
	65	0.11
	70	0.07
	75	0.05

5.3.2.4 Open Flame

The MC and FFMC values were determined for an ignition probability of 70% (Table 5.13). They are reported for scenarios without wind and with a wind speed of 1 m/s. The model was highly significant, indicating reliable predictive power and that the model can be used by managers with a high degree of confidence. Table 5.14 presents several probability of ignition values for various MC values.

Table 5.13 Decision-support table with MC and FFMC values for a 70% probability of grass ignition from open flame.

	Ignition Thresholds for Management Applications (P(y=1) = 0.70)	
	MC (%)	FFMC
No Wind	25	78
Wind = 1 m/s	53	59

Table 5.14 Decision-support table of ignition probabilities for grass fuels from open flame, depending on MC, and wind speed.

		No Wind	Wind = 1 m/s
MC (%)	1	1.00	1.00
	5	1.00	1.00
	10	0.99	1.00
	15	0.98	1.00
	20	0.91	1.00
	25	0.69	1.00
	30	0.34	1.00
	35	0.10	1.00
	40	0.03	0.99
	45	0.01	0.96
	50	0.00	0.83
	55	0.00	0.53
	60	0.00	0.20
	65	0.00	0.05
	70	0.00	0.01
	75	0.00	0.00

Chapter 6. Conclusions, Management Implications, and Recommendations

Research presented in this thesis investigated conditions for ignition success in grassland fuels. Several different ignition sources were reviewed, and five experiments were designed to simulate dangerous ignition sources of concern to DOC. The experimental designs were innovative, and research methods and findings can be applied to grasses and similar fine fuels. Ignition probabilities were calculated for each of the ignition sources investigated, and can be applied to fire management risk-reduction strategies. The work should be extended to include an increased number of experiments and scenarios. This chapter provides a concise summary of conditions required for ignition from the various sources. The implications for fire management in New Zealand are discussed, along with recommendations for further research. The five research questions (Q) from Chapter One are provided below, with answers (A):

1) Q: At what moisture content levels will grass fuels ignite from different ignition sources?
   A: Moisture content (MC) levels are presented below (Table 6.1).

Table 6.1 MC levels for each ignition source where successful ignition occurred.

Ignition Source	MC levels at which successful igniton occurred (%)
Hot Metal	up to 111
Hot Carbon Emissions	up to 116
Metal Sparks	up to 69
Organic Embers	no ignitions
Open Flame	below 54

2) Q: What is the time-to-ignition using the different ignition sources?
   A: Time-to-ignition varied for each ignition source, and was not related to the MC level of the sample ($R^2 < 0.1$). Minimum and average ignition times are presented below (Table 6.2). For hot metal, no relationship was found between time-to-ignition and hot metal temperature. Furthermore, wind speed did not affect the relationships for any ignition source except hot metal, where goodness-of-fit was slightly higher ($R^2 \sim 0.3$) but remained too low to report significance.

Table 6.2 Minimum and average time-to-ignition values for each tested ignition source.

Ignition Source	Minimum time-to-ignition values (s)	Average time-to-ignition values (s)
Hot Metal	35	224 ± 9 s.e.
Hot Carbon Emissions	35	162 ± 14 s.e.
Metal Sparks	7	20.7 ± 0.8 s.e.
Organic Embers	no ignitions	no ignitions
Open Flame	0	0.3 ± 0.1 s.e.

3) Q: At what contact temperatures will grass fuels ignite?
   A: The hot metal experimental results suggested that grass fuels can ignite at contact temperatures as low as 390ºC.

4) Q: At what carbon (vehicle exhaust emission) temperatures will grass fuels ignite?
   A: The laboratory experiments were conducted at 200ºC, and 54% of samples ignited. The exhaust gas of the Nissan Navara 2006, used for the field experiments, only reached as high as 115ºC, and no ignitions were observed. Further study, with various exhaust temperatures is required before this question can be answered with certainty.

5) Q: Under what conditions will grass fuels ignite from sparks (metal and organic)?
   A: For metal sparks, grass samples have a 50% probability of ignition at a MC level of 37%. This was found for an ambient temperature range of 18.5 to 20.1ºC and RH range of 31 to 54%, using a 230 mm-Makita hand-held grinder (model GA9040S) to grind steel for ≤ 30 seconds.
   For organic sparks (embers), no ignitions were observed from the hot organic disks that were created in the laboratory. Further study of this ignition source is required.

6.1 Summary of Key Findings

The key findings are summarised for each ignition source. Each ignition source was investigated through experiments that were developed in the laboratory. Tussock and exotic grass samples were tested in their natural vertical orientation, and no significant difference in ignition behaviour was found. Wind speed and sample MC were varied, while ambient temperature and RH were kept relatively constant. The ignition thresholds are presented below and in Table 4.18. Comparison with previous work indicated that both fuel orientation and ignition source location have an effect on ignition behaviour. Field experiments were conducted to validate findings from laboratory results.

6.1.1 Hot Metal

Off-road vehicle exhaust systems can reach up to 585ºC, as indicated by previous studies (Chapter Two). According to temperature measurements in this study, an unloaded, fully maintained Nissan Navara 2006, manual diesel reached 398ºC at the manifold while driving. This temperature corresponds to the lowest temperature required for a 50% probability of ignition from hot metal, as predicted by the logistic regression model. However, it is unlikely that grass will contact the manifold of a utility vehicle, as it is further away from the ground than other parts of the exhaust system. Data from driving on off-road tracks and gravel roads suggested that most locations on the Nissan's exhaust system remained below 300ºC while driving, and decreased to less than 230ºC when in idle. These observations, and results from the hot metal experiments imply that utility trucks similar to the Nissan have a very low to no probability of igniting dead grass at any MC level. However, further work is required to test vehicle exhaust system temperatures under a greater range of conditions, such as fully laden vehicles that may reach higher exhaust system temperatures due to a higher engine workload.

Conversely, ATVs have high potential to cause ignitions in grassland fuels. The field experiment recorded exhaust system temperatures between 427 and 512ºC at the manifold, after only 17 minutes of driving on gravel roads. Successful ignitions were observed for all samples tested. The temperatures were within the ignition thresholds reported for the vertical hot plate orientation with wind speeds of 1 or 2 m/s. Hot exhaust systems of trail bikes and industrial equipment should therefore be considered to pose high ignition risk.

The ignitibility of grass samples was tested by using a copper hot plate in two orientations: vertical and horizontal. At a MC of 1%, the ignition thresholds for a probability of ignition of 50% were 398 and 421ºC for a vertical hot plate orientation and wind speeds of 2 and 1 m/s respectively. For a horizontal hot plate orientation with wind speeds of 2 and 1 m/s, the thresholds (for a MC of 1%) were 429 and 452ºC respectively. For both hot plate orientations, there was very low to no probability of ignition when wind was not present. The results and model (which correctly predicted 77% of the observations) indicated that ignitions can occur at MC levels up to at least 100%, for a five minute exposure time.

Comparison with other studies suggested that grass orientation affects ignition success. Grass in its natural standing orientation appeared to require higher contact temperatures before ignition could occur, which was attributed to a lower flow of oxygen through the sample. Hot plate orientation also affected ignition probability, where samples required progressively higher metal temperatures for ignition from hot metal at the following locations: on top of the hot plate < adjacent to the hot plate < underneath the hot plate. This is likely due to the buoyancy of the convective heat plume in relation to hot plate orientation.

6.1.2 Hot Carbon Emissions

Laboratory and field experiments were designed to investigate ignition capabilities of hot carbon emissions from vehicle exhausts for grass fuels at various MC levels. In the laboratory, hot carbon particles of 1.0 mm diameter ignited grass samples at up to 116% MC; however, this was only true for a hot air flow of 3.7 m/s at 200ºC. In the field, no ignitions were successful, with hot exhaust gas at an average of 105ºC. Air flow was not measured in the field. It was difficult to compare results between laboratory and field trials, as experimental methods varied slightly. In this study, the vehicle (Nissan Navara 2006) used for the field experiment was properly maintained, and was not emitting sparks, nor exhibiting high exhaust gas temperatures. Poorly maintained vehicles may reach higher exhaust gas temperatures. Further research is required for this ignition source, as outlined in section 6.3.

Two models were statistically significant, but they were weak and had large error associated with predictions. The preferred model was not as statistically significant as the secondary model, but can be applied to a wider range of environmental conditions. The secondary model can only be used when conditions are between 18.5 and 20.1ºC ambient temperature, and 31 and 54% RH. The ignition thresholds for a probability of ignition of 50% were 65% MC for the preferred model and 62% MC for the secondary model, indicating that there was little difference between models. The preferred model correctly predicted 69% of the experimental observations, and the secondary model correctly predicted 78%.

Findings from two previous studies were in accordance with results, where hot carbon particles between 1 and 3 mm were found to ignite grass fuels. Tussock grass blades have a smoother texture than exotic grasses, which influenced the ability of hot carbon particles to land and remain on tussock grass samples. The higher percentage of ignitions observed for exotic samples was attributed to this difference in sample characteristics.

6.1.3 Metal Sparks

Surprisingly, metal sparks ignited samples at higher MC levels than expected (up to 69% vs. 15%). Results affirmed citations that metal sparks are a significant ignition source from grinding operations. No previous studies have explored the ignition behaviour of metal sparks with grassland fuels; therefore, findings have furthered scientific knowledge tremendously, providing considerable insight for fire management.

The probability of ignition success model was highly significant, and predicted a 50% ignition probability of 37% MC, regardless of wind speed. The model correctly predicted 90% of the experimental observations. During the experimental trials, some sparks did not land on the samples. This was attributed to variability in the stream of sparks, as grinding caused sparks to fly in many directions. Unfortunately this could not be quantified; but, the model was highly significant regardless of this observation. Furthermore, this variability was representative of field conditions. All samples tested in the field ignited, with the model correctly predicting ignition success.

6.1.4 Organic Embers

Further research is required before conclusions can be made regarding ignition thresholds of organic embers, which were meant to simulate smouldering organic matter that had fallen off a vehicle. Laboratory simulation was difficult, and the organic disks did not contain enough fuel to sustain smouldering; therefore, once removed from the heat source and placed on the samples, they cooled and none of the samples ignited. No other experiments similar to this have been previously conducted, and further investigation should consider field tests with several different vehicles and situations, as outlined in section 6.3.

6.1.5 Open Flame

The lighter-sized flame ignited samples at MC levels up to 54% for light wind (1 m/s) conditions, and at MC levels up to 32% without wind. None of the previous studies had investigated the ignition behaviour of dead grass under the same conditions. One study reported a threshold (38% MC) for live and dead grass with various wind speeds up to 11.1 m/s. Without wind, other studies reported higher thresholds in comparison with this study, but this was attributed to horizontally oriented grass samples (which seem to ignite more readily than vertically oriented samples), and longer flame application which allowed samples to dry sufficiently for successful ignition. This study agrees with reports that flame location influences ignitibility of fuel, where ignition occurs more readily when the flame is located within or adjacent to the fuel.

The probability of ignition model was highly significant, and was the strongest of all models in this study. However, predictions for a wind speed of 2 m/s were not statistically significant, so this wind speed was not included in the model. The non-significance was attributed to the wind blowing the flame out during trials, causing inconsistency in the results. The ignition thresholds for a probability of ignition of 50%, for conditions with a wind speed of 1 m/s and without wind, were 28 and 55% MC respectively. The model correctly predicted 97% of the experimental observations. All samples tested in the field ignited, with the model correctly predicting ignition success.

6.2 Management Implications for New Zealand Grasslands

This work provided an indication of some activities that are associated with the highest wildland fire risk in grasslands. This is very important from a fire management perspective, as different levels of control can now be established depending on the level of risk associated with the activity. This section relates the experimental results to the simulated ignition sources, and their associated activities, which puts fire risk into perspective. A review of the decision-support tools is also included, as presented in detail in Chapter Five. The results and decision-support tools also provide insight for fire investigators to rule out or verify certain ignition sources as fire causes.

The level of risk for each ignition source was ranked from one to four, where level four was the most risky (Table 6.3). The risk from organic embers was not considered because further work is needed before results can be used for field application. Explanation of activities linked with these risks is provided below.

Table 6.3 Risk ranking for four ignition sources.

Ignition Source	Risk Ranking (where 4 is most risky and 1 is least)
Open Flame	4
Hot Metal	3
Metal Sparks	2
Hot Carbon Emissions	1

The riskiest ignition source was open flame (risk ranking = 4), as it will always ignite fuels under the right conditions. With light wind, ignition can occur for fuels at MC values up to 55%. Above these values, open flame has the potential to dry fuels to their ignition point. Recreational users need to be aware of the dangers associated with open flame sources, especially gas cookers. The use of open flame can be banned or restricted during periods of high fire danger, however, managers should appoint extra fire suppression teams to stand-by when fire danger is high in case of careless or ignorant users.

Hot metal was ranked the second riskiest ignition source (risk ranking = 3), as it has the potential to ignite dead grass fuel at high MC levels. However, not all hot metal ignition sources are capable of reaching temperatures sufficient to cause successful ignitions in light wind conditions. Furthermore, ignition success depends on adequate contact time between the hot metal and cured grass. The riskiest activities include the use of two-wheel trail bikes under rough conditions such as steep terrain, or the use of ATVs in long dead grass. These off-road vehicles are more likely to ignite grass, as their exhaust systems do reach temperatures sufficient for grass fuel ignition. Maintained, modern off-road utility vehicles have low risk of igniting grass fuels, because grass fuels are unlikely to contact the hottest locations of those exhaust systems, which generally remain below temperatures required for ignition. Therefore, they should not be subjected to activity controls unless ambient temperature is high, RH is low, and MC is low (or FFMC is high).

The third riskiest ignition source was metal sparks (risk ranking = 2), which surprisingly has a 50% ignition probability for fuels at a 37% MC level. The MC level for a 70% ignition probability was also high at 26%, or 77 FFMC. At these moisture levels, grinding operations could be restricted, or resources could be readily available to prevent fire spread if an ignition were to occur.

The least risky ignition source was carbon emissions (risk ranking = 1). Grass fuels were predicted to have a 50% probability of ignition from hot carbon sparks and hot exhaust gas at 200ºC. However, it is unlikely for a maintained, modern off-road utility vehicle to emit exhaust gas this hot. Driving these vehicle-types should not be prevented; however, during periods of very high fire danger, resources should be available to suppress fires from any ignitions that occur. A condition of entry could be implemented, which would only allow access for vehicles which have spark arresters fitted. Further research is needed for this ignition source, however poorly maintained vehicles should be considered to pose higher ignition risks compared with properly maintained vehicles.

Decision-support tools were created for each ignition source tested (Chapter Five), except organic embers which did not ignite grass samples. They provide an indication of conditions which are conducive to a 70% probability of ignition for all four ignition sources (Tables 5.7, 5.10, and 5.13, and subsection 5.3.2.3). For hot metal, thresholds are reported in terms of a MC value of 1%, but MC will likely never reach this value in field conditions, and the lowest MC value is approximately 3%; therefore, the reported hot metal temperatures should be considered conservative estimates. Also, tables are included for each ignition source which report different probability values for various conditions (Tables 5.8, 5.9, 5.11, 5.12, and 5.14). These tools can now be used by fire managers to aid decision-making processes for activity controls in different environmental conditions.

6.3 Key Recommendations for Future Work

This research has provided an increased knowledge of the ignition behaviour of grassland fuels from various ignition sources. Further research is necessary to validate this knowledge, and improve the current models of ignition probability. Key research recommendations are:

- Undertake research to investigate current and new methods for ignition testing so that appropriate universal testing procedures can be developed. This would facilitate comparisons between studies.

- Repeat these tests using different types of grass fuel samples, including other orientations (horizontal, 45º angle), various lengths, litter, various cured states (from 0 – 100%), and larger or smaller sample sizes.

- Repeat these tests under various environmental conditions (in the laboratory and field) including higher and lower ambient temperatures, higher and lower RH levels, and higher wind speeds.

- Repeat these tests with longer exposure times for each trial.

- Conduct more field experiments, with grass samples *in situ*, for each ignition source.

- For field experiments, increase the number of repetitions and sample sizes, to gain a better understanding of ignition behaviour under various environmental conditions.

- Extend the research to model the probability of fire spread given the initial MC of surrounding fuels.

The following recommendations are for hot metal ignition sources:

- A wider range of hot plate temperatures should be tested at different wind speeds and hot plate orientations.

- In order to rule out outliers, a higher number of trials need to be conducted, particularly as only 16% of all tested samples ignited.

- Tests should be carried out with hot plate temperatures higher than 500ºC, both with and without the presence of wind.

- Wind speed should be measured at the exhaust system level of several vehicles in the field on several days, under a range of environmental conditions. This would give an indication of the range of wind speeds that would be required for further testing.

- It would be useful to repeat the tests with samples conditioned to MC values between 20 and 50%, to further improve the probability model.

- Increase the number and types of vehicles tested with grass samples in the field, including two-wheel trail bikes, poorly maintained vehicles, older vehicles, fully loaded vehicles or vehicles pulling trailers, various makes and models, and rough versus smooth terrain. Results from tests using these vehicle-types and conditions would provide managers with well-rounded results from different exhaust systems.

The following recommendations are for hot carbon emissions ignition sources:

- Repeat the trials with higher and lower exhaust gas temperatures (50 to 350ºC), with higher exhaust gas speeds (up to 30 m/s), and with or without the addition of hot carbon sparks (as maintained vehicles usually do not emit hot carbon particles from the exhaust system).

- Quantify the number of sparks that land and remain on grass samples, and analyse the results to examine how readily hot carbon particles adhere to different grass types.

- A diverse range of vehicles should be used for field experiments, as described for hot metal. Exhaust systems of some of these vehicles should either produce sparks, or have been altered to produce sparks.

The following recommendations are for metal sparks ignition sources:

- Repeat the trials with various grinder sizes, speeds, makes and models. If there is a difference in ignition behaviour between grinder-type, managers could then specify which grinders are safe to use in certain environmental conditions.

- Conduct more trials at MC values closer to the ignition threshold value (37% MC).

The following recommendations are for organic embers ignition sources:

- Future investigation would best be conducted under field conditions, which could involve a variety of makes and ages of utility vehicles, ATVs, and trail bikes, which have had their exhaust systems either covered with mud and grass fuels, or have been submerged into different vegetation types. The vehicles could then be driven around a sample area for various time periods until the vegetation is observed to smoulder and/or fall off.

The following recommendations are for open flame ignition sources:

- In order to improve predictive power, more repetitions are required with samples conditioned to various MC levels between 10 to 70%.

- Exposure time should be increased until successful ignition is observed for samples with higher MC levels. Results could be related to moisture of extinction values reported by various researchers, which would aid current knowledge for management decisions.

- Test the resilience of various open flame sources (e.g., gas cookers and various types of lighters) to remain lit at various wind speeds, and repeat the tests using different open flame sources.

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