Fire ecology and management information transfer from Western Australia to New Zealand

SCIENCE & RESEARCH INTERNAL REPORT NO.166

Department of Conservation
Te Papa Atawhai

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Published by
Department of Conservation
P.O. Box 10-420
Wellington, New Zealand

Science & Research Internal Reports are written by DOC staff and others on matters which are on-going within the Department. They include reports on conferences, workshops, and study tours, and also work in progress. *Internal Reports* are not normally subject to peer review.

ISSN 0114-2798
ISBN 0-478-21795-1

Cataloguing in Publication
Burrows, N. D.
Fire ecology and management information transfer from Western Australia to New Zealand / N.D. Burrows. Wellington, N.Z. : Dept. of Conservation, 1999.
1 v. ; 30 cm. (Science & Research internal report, 0114-2798 ; no. 166.)
Includes bibliographical references.
ISBN 0478217951
1. Fire ecology. 2. Fire management. I. Title. II. Series: Science and Research internal report ; no. 166.
574.5222 632.18 20
zbn99-006063

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Abstract

Fires have occurred in New Zealand for millions of years, but their frequency and severity have increased dramatically since human settlement. The Department of Conservation deals with 100-150 fires each year at an average annual suppression cost of about $300,000. The Department has twin responsibilities with respect to fire. It is a Forest and Rural Fire Authority and has a policy to extinguish all fires on or near land that it administers, principally to protect life and property. In addition, the Department must manage the land it administers to protect conservation values. Some ecosystems, such as native forest are destroyed by fire. Others, such as tussock grasslands and some wetlands, are fire-induced and depend on fire, if only very occasionally, for their maintenance.

Fire is clearly an important influence on conservation values and a potential threat to life and property. However, our understanding of its effects on biodiversity and on ecosystem processes is insufficient to effectively manage native ecosystems with respect to fire.

The objectives of this report were to assist with the investigation of the role of fire in the management of protected natural areas for specific conservation values, and aid the development of appropriate protocols for monitoring the effects of fire on vegetation and invertebrates.

It was concluded that climatic, edaphic, and biological indicators suggest that New Zealand's fire environment could be rated as low to moderate, compared with other bio-regions of the world.

However, fire has been an important factor in creating and maintaining many ecosystems, usually at the expense of native forests, and remnant native forests are highly sensitive to fire. Moreover, wildfires which threaten human life and property and conservation values will continue to occur.

Consequently, a systematic wildfire risk analysis for New Zealand should be given a high priority. This can be used to determine appropriate pre-suppression and suppression actions and to prioritise resource allocations.

DOC needs to establish a clear policy and management objectives in relation to conservation of flammable vegetation types, including tussock grasslands, shrublands, and some wetlands. Fire management issues need to be incorporated into each level of land management planning and to be broadened to include fire ecology.

Prescribed fire can be used in certain ecosystems to (a) reduce the negative impacts of wildfires by managing fuel buildup and (b) maintain and enhance successional diversity.

An ongoing fire ecology research and monitoring programme will provide the necessary information about the role of fire in natural ecosystems.

Recognition and definition of fire issues, the formulation of clear fire management policies and objectives underpinned by sound science, and a well trained and well equipped firefighting force will reduce the risk and impact of a major fire.

1. Introduction

The Department of Conservation (DOC) is responsible for the conservation of New Zealand's natural and historic resources. DOC manages about one-third of New Zealand's land area, including national parks, forest parks, reserves, river margins, some coastline and many offshore islands (Department of Conservation 1996). Fire is recognised as a threat to human life and property and to nature conservation values. Many ecosystems such as tussock grasslands and some wetlands are fire-induced and depend on fire for their maintenance.

DOC fire policy is to extinguish fires on or near land it administers. Clearly, the primary objective of this policy is to minimise the threat posed by wildfire to human life and property and to conservation values. Prescribed fire is not used as a management tool to help achieve these objectives, in part because a firm understanding of the effects of fire on biodiversity and on ecosystem processes is lacking.

Recognising the importance of fire to conservation and the potential threat of fires to life and property, DOC has identified the need for a more comprehensive scientific understanding of the role of fire in New Zealand's natural ecosystems.

The objectives of this review were to assist with:

- The investigation of the role of fire in the management of "protected natural areas" for specific conservation values
- The development of appropriate protocols for monitoring the effects of fire on vegetation and invertebrates

This report covers:

- New Zealand's fire climate in comparison with that of Western Australia
- Findings from field inspections and discussions in New Zealand, including the role that fire has in helping or hindering management of an area for specific conservation values
- Standard methodology for monitoring the effects of fire on vegetation and invertebrates
- Advice to the Department to guide the development of a robust fire policy.

2. The fire environment

The fire environment, or the prominence of fire as a natural environmental factor, is influenced by the nature of the climate, the vegetation, and the availability of ignition sources. The frequency with which fires are likely to occur, and their scale, is determined by these factors. This broad characterisation of the fire environment is useful for comparing different bioregions, for understanding the role that fire plays in moulding ecosystems, its role in maintaining ecosystems, and the risk that fire poses to human life and property values.

2.1 EVIDENCE OF PAST FIRES IN NEW ZEALAND

The historical evidence of fire in New Zealand has received considerable scientific attention and has been reviewed by Basher *et al.* (1990) and Allen *et al.* (1995). Most authors conclude that while fires occurred for many millions of years before human settlement, they were too infrequent (estimated to be about every 500 years, based largely on radiocarbon dating of subfossil remains and on pollen analysis) to be of major ecological significance (Allen *et al.* 1995 citing Wardle 1994). This view may underestimate the role of fire. Infrequent drying of rainforests and the associated fires, probably caused by volcanic activity or lightning, may have had an impact on both the structure and floristic composition of the forests which once occupied 85-90% of New Zealand (McGlone 1989).

Analyses of subfossil charcoal and pollen diagrams by a number of workers indicate an increase in the frequency of natural fires over the period 3,000-1,000 years before present (BP), together with deforestation (see review by Allen *et al.* 1995). Pollen records indicate an increase in grassland and fernlands during this period. This may have been associated with increasing aridity or ignition sources, or both.

With the arrival of Polynesians, the level of deforestation, particularly in the eastern South Island, escalated dramatically, reaching a peak between 700 and 500 years BP (Allen *et al.* 1995). Increases in fern spores, grass pollen and charcoal over this period have been interpreted as frequent burning by Polynesians to maintain fernlands and grasslands. The relative speed and scale of deforestation by Polynesian fires suggests that the trend of increasing periods of aridity continued through this period. The size and frequency of destructive forest fires after human settlement appears to have been a result of more fires being lit. It has been estimated that, by the time of European settlement, about 40-50% of the original forest area had been transformed by frequent fire to tussock grasslands, fernlands and shrublands (Masters *et al.* 1957, Basher *et al.* 1990). Following European settlement a further 20-30% of mature and regenerating forests were cleared and burnt for agriculture (McGlone 1983).

2.2 FIRE CLIMATE

The composition and distribution of flora and fauna is largely determined by climate, soils and topography. Fire is an important factor affecting biodiversity in climatic regions around the world which experience seasonal or periodic drying or drought. The historical frequency and scale of fire (i.e., the fire environment) varies considerably between the world's bioclimatic regions. For example, in ecosystems such as temperate and tropical rainforests, fires may occur at as great an interval as 200 years, whereas in grasslands or savanna woodlands, or in regions which experience seasonal wetting and drying, fires may occur as regularly as every 1 to 3 years. Given the availability of an ignition source and sufficient vegetation as fuel, the frequency with which an ecosystem is likely to carry fire depends on climate, especially the severity, periodicity and duration of drought.

New Zealand's climate is dominated by its southerly latitudes, the main mountain divide (Southern Alps in the South Island), and its proximity to the sea (no part of New Zealand is further than 130 km from the sea (Maunder 1971)). Average annual rainfall varies from about 7,000 mm at Homer Tunnel to 335 mm at Alexandra, Central Otago. The climatic regions Canterbury Plains-North Otago and Mackenzie Country-Central Otago, identified by Maunder (1971), experience the lowest annual rainfall (500-750 mm over the entire region). In Central Otago, evaporation is more than about twice the rainfall whereas in most other regions, evaporation is usually less than rainfall (Maunder 1971). The other "dry" climatic regions, which are encompassed by the 1,000-1,500 mm isohyet, are Gisborne, with northern and central Hawke's Bay, and southern Hawke's Bay and Wairarapa. Not surprisingly, these drier climatic regions of New Zealand also experience the most severe fire climate (Pearce 1996).

If New Zealand's fire climate is broadly compared with that of Western Australia, it could be rated as low to medium.

Pearce (1996) noted that, while New Zealand does not have the worst fire climate in the world, it experiences around 2,000 vegetation fires each year. Hilliard (1997) reported that over the ten year period from 1987-1997, 1,570 fires occurred on land administered by DOC, burning 27,042 ha (mean fire size 13.5 ha). The suppression cost was about $4.5 million. Most fires were caused by humans. Although 2,000 ignitions each year is high, the actual area burned is comparatively low. Over the same period, the Western Australian Department of Conservation and Land Management, which administers about 20 million ha (a little over double the area managed by DOC), reported 4,330 wildfires which burned a total of 2.985 million ha (mean fire size 700 ha). About 20% of these fires were caused by lightning. The rate of ignitions per unit of land area is similar in both cases (about 0.0002 ignitions per hectare), but the total area burned and the average fire size are vastly different. Most of the area burned by wildfires in Western Australia was in the arid and semi-arid region (hummock grasslands and savanna woodlands) remote from population centres and suppression forces.

This simplified comparison of contrasting fire environments highlights a key fire management issue in New Zealand, which is the very high incidence of ignitions caused by humans. This is a concern for the entire community. The high level of ignitions and the relatively small average wildfire size in New Zealand is indicative of either a very effective fire detection and suppression system, or mild weather conditions and hence moderate fire behaviour (so most fires are quickly suppressed), or both. The comparatively mild fire weather usually experienced over most of New Zealand probably assists firefighters. However, with such a high level of ignitions, it is highly probable that multiple wildfire outbreaks during a period of widespread and extended drought will exceed the suppression capability, resulting in large, intense and damaging wildfires.

In the New Zealand context, Bondy (1950) defined drought as a period of at least 15 days in which there is no measurable rainfall, and partial drought as a period of at least 29 consecutive days during which the mean daily rainfall <0.25 mm. Based on available records, Maunder (1971) reports the following major drought periods: 1897/98 Clyde, 1907/08 Moteuka, 1927/28 East Cape; and partial droughts: 1937 Clyde and Blenheim, 1964 Alexandra. The average number of absolute droughts per decade varies from 30 at Clyde in Central Otago and 20 at Napier to 3.4 at Dunedin and 2.7 at Invercargill. Clyde and Central Otago recorded 99 partial droughts in 53 years of record, 22% of these being over 9 weeks and 7% being over 3 months. In central and southern Canterbury and Otago, winter is the most drought-prone period, whereas for other parts of the country, droughts are more likely in summer (Maunder 1971).

Mean annual rainfall alone is not a reliable indicator of the fire climate. For example, the mean annual rainfall for Alexandra is less than half that of Perth, Western Australia, but it is more-or-less evenly distributed throughout the year. On the other hand, Perth has a Mediterranean-type climate with winter rainfall and summer drought. Maximum daily temperatures for Perth are also significantly higher than for Alexandra.

When vegetation has dried sufficiently to burn, wind is an important weather factor affecting fire danger and fire behaviour. Strong winds are a feature of many parts of New Zealand, and it is probably the predominance of cool, moist conditions which modifies the influence of wind speed on daily fire danger rating throughout most parts of the country.

3. Fire ecology

3.1 EXTENT OF ADAPTATION TO FIRE

Few New Zealand forest species show fire adaptations that are common in ecosystems which experience frequent fire (Allen *et al.* 1995 citing Basher *et al.* 1990), such as the dry sclerophyll forests of Australia where fire intervals of from 5 to 20 years are usual. These traits include thick protective bark, serotinous fruits, fire-induced flowering, and the capacity to resprout following fire. However, before human occupation of New Zealand, infrequent drought and fires would have occurred, and they would probably have exerted some selection pressure on forest species and communities and played an important role in determining the composition of modern forests. There is ample evidence that New Zealand's forests have the capacity to persist under a regime of infrequent fire but are not capable of persisting under a frequent fire regime. Therefore, these forests could be described as being adapted to a regime of very infrequent fire.

Although the published data on forest succession are limited, the pre-historical evidence of fire and forest regeneration would support the theory that, after fire, New Zealand rainforests probably follow a typical succession pathway. Communities of coloniser species occupy the site and progressively give way to successor assemblages until a final assemblage, the "climax community", develops; this is capable of persisting until the next fire or other major disturbance (e.g., Calder *et al.* 1992, Rogers & Leathwick 1994). This pattern contrasts with that for fire-prone ecosystems, such as the dry sclerophyll forests of Australia, which display a variety of fire adaptations and do not conform to the succession model. Within a few years after fire, the species composition of these ecosystems closely resembles the pre-fire condition (e.g., Bell & Koch 1980). Unlike continents such as Australia and North America, where drought and fire have played a major role in shaping ecosystems, it has largely been the cold climate, relatively fertile soils, and long geographic isolation which have moulded New Zealand's flora and fauna.

The relatively rapid deforestation by human use of fire, especially in the drier, eastern regions of the country, demonstrates that the forests, particularly beech forests, dry sufficiently to carry fire, and it was probably the low risk of ignition, hence low fire frequency, which preserved these forests prior to human settlement. Once burned, these forests do not have the capacity to quickly recover to their pre-fire state and may take decades or even centuries to attain their former composition and structure. Relatively frequent firing maintains grassland, fernland and shrubland communities, which are early successional stages (except at high altitudes).

Frequent fire has resulted in the dramatic expansion of tussock grasslands at the expense of forests. Forests, which once covered 85–90% of the country, now exist as remnants in many areas, especially in the lowlands, and need protection from fire and other threatening processes. In some parts of the country, tussock grasslands are flammable for an estimated 200 days per year and act as wicks carrying fire upslope into adjoining fire-sensitive forests. Fires burning in tussock grassland usually self-extinguish on reaching the cool, moist forest microclimate. However, in many cases, they burn a short distance into the forest, killing the trees at the forest edge and converting it to shrubland or grassland. Remnant patches of beech forest surrounded by a sea of flammable tussock grassland are highly vulnerable to fires. Although the rate of fire-caused deforestation has declined in recent times, it continues due to unplanned wildfires or escapes from the deliberate burning of grazing land on lower slopes. In the absence of constructed firebreaks, the moist upslope forests are often used as firebreaks, sometimes to their detriment.

Apart from the gradual degradation of forests, particularly at the often sharp forest-shrubland-grassland ecotone, there is also evidence that frequent burning of tussock grasslands for grazing leads to a reduction in floristic diversity and to soil nutrient loss and erosion (see review by Allen *et al.* 1995). This may be occurring on a greater scale than deforestation, and is also of great concern.

A similar pattern of fire-caused degradation appears to be occurring in forest fragments within wetlands and at the margins of forests which surround wetlands.

3.2 MAJOR FIRE-PRONE ECOSYSTEMS

The fire ecology of grasslands, wetlands, and shrublands in New Zealand has been reviewed elsewhere (e.g., Basher *et al.* 1990, McKendry & O'Connor 1990, Working Party on Sustainable Land Management 1994, Boland 1995, Allen *et al.* 1995, and Parliamentary Commissioner for the Environment 1995).

The following is a summary of key ecological and management issues identified by these authors:

Tussock grassland

Over the last decade, about 24% of the total area burnt by wildfire on or near DOC administered land, was tussock grassland (Hilliard 1997). In addition to the thousands of hectares of leasehold land burnt by pastoralists, fire management in this vegetation type is clearly an important issue from protection, conservation and production perspectives. Most of the existing tussock grasslands are fire-induced, but burning of tussock grasslands, particularly in association with pastoralism, is a controversial issue. The literature (e.g., McKendry & O'Connor 1990) raises a number of important scientific and management issues. What are the management objectives? What is the role of fire in maintaining these ecosystems? What is the most appropriate fire regime to ensure the protection/maintenance of biodiversity? In the absence of fire, will these ecosystems eventually progress to shrublands and/or forests? If so, is this desirable or achievable; how much and where? What are the most appropriate fire control strategies in these ecosystems? A firm scientific understanding of these ecosystems is necessary to underpin management.

Daly (1977) recognised 6 types of tussock grasslands based on species composition. These were grouped as either short or tall tussock grasslands, with some degree of separation of these types based on environmental gradients, especially rainfall, altitude and soil fertility. Most tussock grasslands below the tree line are a result of disturbances such as fire, and/or grazing, floods, changing river courses and volcanic activity. The major types of short tussock grassland have been induced by the repeated burning and/or grazing of tall tussock grassland. The short tussock grasslands are thought to be declining in fertility and extent.

All uses of tussock grasslands require active management (Parliamentary Commissioner for the Environment 1995). However, there is a lack of agreement on prescriptions for their conservation and management.

There is an information gap between scientists and land managers. Fire history records are poor. Existing information is not readily accessible. There is a lack of information about the distribution and abundance of species and communities, which hampers decisions about the comprehensiveness, adequacy and representativeness of reserve systems for tussock grasslands.

Grassland fire research in New Zealand has concentrated on snow tussock vegetation, which is now generally on low productivity terrain. Little is known about the effects of fire on red tussock grassland. Many long-term effects are unknown, although it is believed that repeated burning at short intervals leads to soil nutrient loss, erosion, and reduced biodiversity. Soil degradation is a most serious concern. There are conflicting opinions over the interpretation of scientific data on the effects of fire (Parliamentary Commissioner for the Environment 1995).

Woody shrubs are an important floristic and structural element of tussock grasslands and are probably influenced by fire history. In the absence of fire, most tussock grasslands would probably develop to shrublands and to forest, depending on the altitude and the proximity and availability of seed sources. Repeated firing at short intervals can suppress shrub development.

There is some evidence that, at high altitudes, decreased fire frequencies promote the development of woody shrubs such as *Hebe* and *Dracophyllum*. There is anecdotal evidence of an increase in manuka and matagouri on some sites following long fire-free periods. In some areas, kanuka and manuka are often favoured by frequent fire. In other areas, fire exclusion has not resulted in any invasion by scrub species (Dickson *et al.* 1992).

Few native plant species display specific adaptations to fire, although many are able to regenerate following fire. Apart from a few species there is little evidence of a bank of long-lived seeds in the soil, an important attribute in a fire-prone environment. Resprouting is the most common post-fire response strategy in New Zealand tussock grasslands (e.g., snow tussock, silver tussock).

It takes at least 14 to 15 years for *Chionochloa rigida* snow tussock plants to recover to their pre-burn state (nutrient status, flowering phenology) and from 20 to 25 years to reach pre-burn biomass levels. Spring burning has the least detrimental effect on tiller mortality and biomass recovery, with summer/autumn fires having the most detrimental effect.

Recovery is most rapid in the absence of grazing by domestic stock. Small burns are often used to intensify grazing pressure, so the grasslands may be more adversely affected than by large burns.

There is inadequate scientific information on the long-term effects of fire on fauna in tussock grasslands. There are a few published short-term studies, but results are often inconclusive or inconsistent.

Shrublands

Very little fire ecology work (long-term or short-term) has been done on shrublands.

Most of New Zealand's natural temperate shrublands have been reduced substantially by fires lit deliberately to clear land for agriculture or by unplanned wildfires.

Those that remain have largely been converted to manuka- or kanuka-dominated shrublands, which have markedly increased. Fire-induced shrublands are now widespread at the expense of forests.

Frequent burning has often resulted in invasion by exotic species such as lodgepole pine, gorse, heather, sweet briar and *Hakea* species, many of which are better adapted to fire.

Bracken fernland has increased as a result of past Polynesian fires.

Wetlands

There are only a few studies of fire effects in wetlands reported in the literature (e.g., Mark & Smith 1975, Wardle 1977, 1991, Williams *et al.* 1990, Timmins 1992, Clarkson 1997). They are opportunistic studies rather than designed experiments.

The changes in stratigraphy and floristic composition of wetlands observed over time suggests that some contemporary wetlands are fire-induced and are maintained by occasional fires.

Some scientists consider that fires should be excluded from wetlands to allow succession to native-dominated flora except where maintenance of early successional stages was seen as desirable (Clarkson & Stanway 1994).

In addition to the direct effects of fire, the replacement of forests with grasslands, fernlands and shrublands has probably altered local hydrology (and nutrient status) sufficiently to have had an effect on the distribution, structure, and composition of wetlands.

Remnant, naturally occurring pakihi wetlands have high conservation values, and are important for regional biodiversity at the habitat level. They also have considerable scientific value, for example they provide an opportunity to test successional theory and species distribution limits (S. Courtney pers. comm.). In the absence of fire, pakihi is likely to eventually develop to "pakihi forest" (podocarp-dominated), provided that climatic and edaphic factors are conducive to forest formation (S. Courtney pers. comm.). Many are in various states of transition from early successional to late successional stage, depending on disturbance history. However, the altered hydrology in some cases prevents this.

There do not appear to be any plant taxa endemic to pakihi (S. Courtney pers. comm.).

Fire regimes affect the composition and abundance of woody shrubs in West Coast wetlands in the South Island. Fire prevents succession to kahikatea or kahikatea-rimu forest.

Many wetland species are able to regenerate after fire by resprouting or from canopy stored seed. Fires at shorter intervals than the juvenile period of obligate seeders (such as manuka) will diminish these species. Different species regenerate from a variety of subterranean propagules, such as bulbs, taproots, stolons, and rhizomes. However, the shallow rhizomes of some are killed by fires which burn deep into the peat under dry conditions.

Plant cover was reduced by 20% by a fire in a *Sphagnum*-wire rush bog, but recovered to 90% within 4 years. The immediate post-burn state was floristically different from the pre-burn state, but long-term was likely to approach the pre-burn state. Species diversity on drier parts of the wetland increased significantly after the fire, then declined as fire ephemerals, such as herbs and grasses, died (Timmins 1992).

Cushion bog is sensitive to fire, taking many years to recover.

Woody and herbaceous weeds often invade wetlands after disturbance such as fire. Some (e.g., gorse) are better adapted to fire even than well adapted wetland species, so use of fire to manage the vegetation would also entail managing the weeds.

There has been little research on the effects of fire on wetland fauna. Some pakihi are important habitats for rare taxa such as fernbird, and green gecko.

4. Fire management

The primary fire control responsibilities of DOC, as defined by the Forest and Rural Fires Act (1977), include:

- The prevention, detection, control, restriction, suppression and extinction of fire
- The protection of life and property from fire

Clearly, DOC has a legal and moral obligation to professionally manage fire for the protection of human life and property, both on and off the land it administers.

Under the Conservation Act 1987, DOC is also responsible for the protection of conservation values on lands it administers. Although it would be possible to use prescribed burning to help to maintain ecosystems that have been created by continued past fire events, DOC has usually followed a fire suppression policy in the absence of comprehensive information about the effects of further burning on conservation values and invading species.

5. Fire prevention and control

The commonly held view, both in New Zealand and abroad, is that New Zealand does not have a "fire problem". DOC deals with 100–150 fires each year and the average annual fire suppression costs are about $300,000. The social, economic and ecological impact of fires in any fire-prone environment is spatially and temporally highly variable, reflecting variability of weather patterns and natural ecosystems. Occasional periods of extended drought have resulted, and will continue to result, in severe fire situations. For example, Hilliard (1997) reports that a single wildfire in 1983 cost more than $1 million to suppress. While the suppression costs are relatively easy to identify, the social and environmental costs are less tangible, but are nonetheless real. These statistics do not prove that New Zealand has a "fire problem", but they demonstrate that fire is a serious management issue.

5.1 MONITORING DROUGHT

Deforestation by Polynesian and European fire and historical documentation of wildfires in a range of vegetation/fuel types is clear evidence that damaging and uncontrollable wildfires have occurred and will occur from time to time (e.g., see Alexander & Pearce 1992, Fogarty 1994, and others).

As widespread drought is the single most important factor which is likely to result in a wildfire crisis, a system for monitoring and quantifying the seasonal build-up of drought across the country should be developed. This, together with daily ratings of fire danger, will provide warnings of the severity of the impending fire season and allow better fire planning and preparedness at the national level. The Soil Dryness Index (Mount 1972, Burrows 1987) developed for fire control in Tasmania could well be applicable to fire control in New Zealand.

Although New Zealand's fire climate could be characterised as low to medium, this is, to some extent, offset by several biogeographical factors:

- There are expanses of flammable fuel (especially tussock grassland, many wetlands, and shrubland).
- Most natural ecosystems, particularly forests, are fire-sensitive, and forests are usually converted to grassland or shrubland following fire.
- Rugged and often inaccessible terrain makes fire suppression difficult and dangerous.

5.2 QUANTIFYING FIRE RISK

These factors suggest that there is a need to objectively assess and quantify the risk posed by fire. A nationwide assessment of ignition potential, fire behaviour potential, values at risk and suppression capacity, needs to be brought together in a systematic way. A comprehensive and systematic regional wildfire risk analysis is required to quantify the risk posed by fire to human life and property and conservation values. Such an analysis should be undertaken as a matter of priority. This will greatly assist with formulating fire management policy, establishing inter-agency agreements, setting fire management and research priorities, and allocating appropriate resources. The process of fire risk analysis is important as it provides a rational and politically transparent framework upon which fire policy and management decisions are based.

The first step in managing the conservation estate, whether it be fire management or otherwise, is to understand the distribution of species and habitats. With respect to fire-induced communities, it is important to understand the range of habitat or vegetation types, the current successional state (post-fire maturity) of these types, and their extent and distribution. This basic information is necessary whether the management objective is to maintain a level of successional diversity within these vegetation types or to protect certain types from fire. Decisions can then be made about the representativeness, adequacy, and comprehensiveness of successional diversity within these types. This will guide decisions about where and when to introduce or to exclude fire and provide a basis for selecting study sites of known but different management histories. A database (GIS environment) of important fire-induced wetland, tussock grassland and shrubland vegetation types administered by DOC should be assembled. Baseline information should include location (a map), special features, management history (including fire) and any other biological or ecological information available for the site.

5.3 FUEL ACCUMULATION

The rate of post-fire biomass accumulation provides information about site productivity and the build-up of fuel. The quantity and structure of the vegetation, or fuel, affects the behaviour, suppression difficulty and damage potential of wildfires. Fuel accumulation information can assist with appraising the wildfire threat, the potential fire behaviour and with decisions about how, when and where to take measures to reduce fuel levels, including if and when to prescribe burn. DOC, in consultation and collaboration with other rural fire authorities, should develop fuel accumulation models for major flammable vegetation types. This can be achieved by sampling a range of comparable habitat types with known but different times since fire (space-for-time).

6. Fire as a conservation tool

DOC has been cautious in its fire management objectives in relation to conservation of flammable vegetation types, including tussock grasslands, shrublands, and some wetlands (see report of the Office of the Parliamentary Commissioner for the Environment 1995). Scientists have recommended a "conservative" approach to fire management of tussock grasslands because of the paucity of scientific knowledge about the role of fire in these ecosystems (e.g., Basher *et al.* 1990). "Conservative" management is not defined, but probably means minimising disturbance to these ecosystems, including fire. It could be argued, however, that a "conservative" approach would be to continue to emulate the fire practices which have produced these ecosystems over the last 700 years or so (on land now administered by DOC) and over the last 150 years or so on pastoral leases.

Allen *et al.* (1990) noted that "In the absence of management to maintain grassland, shrubland and wetland communities below the treeline in their present state, they will continually be transformed through successional processes." However, with the possible exception of ecotones, it is unlikely that tussock grasslands will progress along the classic successional pathway to shrublands and forests, despite the current fire suppression policy. Not only the extent of these grasslands and the absence of nearby seed sources from successional species, but also the inevitable deliberate or accidental firing will ensure that these ecosystems will probably remain grasslands for the foreseeable future.

6.1 FIRE ECOLOGY RESEARCH PRIORITIES

The above summary of what is known and not known about different types of fire-induced ecological communities clearly identifies a need to increase the level of understanding of fire ecology in New Zealand. All of the published fire ecology studies are opportunistic, post-fire observations. While this level of information is valuable, there is a need for well designed, controlled fire ecology experiments to systematically test hypotheses and to investigate the role of fire in New Zealand ecosystems.

Research effort needs to focus initially on those issues which are closely aligned with DOC's mission, that is, research should be relevant, practical, achievable and cost efficient. DOC has a limited capacity to conduct in-house research so collaborative research programmes with other research institutes, such as universities, New Zealand Forest Research Institute, and Landcare Research, is a very effective means of gaining knowledge. Collaboration can take many forms including direct funding assistance, collaboration on research projects and support in kind, such as providing access to study sites and facilities for post-graduate fire projects.

The level of scientific interest in fire ecology within New Zealand's scientific community and fire ecology research should be integrated across agencies. A

National Fire Research Working Group or network should be established in New Zealand to promote fire science, to identify gaps in knowledge and opportunities for collaboration, to exchange ideas, to disseminate information, to integrate research activities and to attract research funding.

New Zealand fire scientists will also benefit by developing networks with the international fire science community. Although findings from one bio-region cannot always be reliably transferred to another, scientific methods of investigating fire effects, with or without modification, can have wide application. DOC should consider an exchange of fire research staff with the Western Australian Department of Land Management to provide an opportunity for a cross-flow of knowledge and ideas relevant to fire research methods and fire management.

6.2 DOC FIRE RESEARCH STRATEGY

The Department's draft fire research plan identifies research areas and ranks these in order of priority based on the urgency and importance of the information to DOC (Timmins, S.; Hilliard, K. 1997. Fire Ecology and Control Research Plan 1997-2006. Unpublished draft report held by Science & Research Unit, Department of Conservation, Wellington). The following comments and recommendations are aimed at complementing this plan, which is comprehensive and soundly based.

There are two major approaches to gathering fire ecology information. In BACI (before, after, control, impact) experiments, plots are measured before and after treatment, and there are control plots from which the impact of treatment can be assessed. In space-for-time (SFT) studies, similar habitat types of known but different time since fire (or other disturbance) are studied contemporaneously in order to understand post-fire ecosystem dynamics. Both techniques have advantages and disadvantages.

Experimental fire research is usually costly and has an element of risk. An important advantage of SFT studies is that valuable information about the temporal and spatial effects of fire can be obtained quickly and relatively inexpensively. Although SFT studies assume inter-site differences between the organisms or processes under investigation are due to different management histories or disturbance regimes, this limitation can be partly overcome by careful site selection to optimise biogeological similarities, and by sufficient replication.

These studies would greatly assist with focusing of experimental research. One of the outcomes of establishing a national network for fire research is that it will provide a framework for selecting sites for SFT investigations. A major, national and multi-agency space-for-time investigation of the impacts of fire on native communities, species and processes should be undertaken in a systematic manner as a matter of priority. This investigation should be supported by a limited but sharply focused number of designed experiments.

A detailed and multi-disciplinary experiment with both fire ecology and fire behaviour objectives is already planned for tall tussock grasslands. It is designed to investigate the effects of fire on aspects of nutrient cycling, vegetation floristics and structure, and invertebrates. It will be the most comprehensive and thorough fire ecology research programme to be undertaken in New Zealand. The fire ecology experiment designed to investigate the impacts of fire on tall tussock grasslands that has been proposed is of national importance and should be strongly supported by DOC.

DOC should consider employing a fire ecologist to progress the development and implementation of the Department's fire research plan, to develop internal and external linkages and to provide scientific advice to DOC on fire management issues.

6.3 BIOLOGICAL INDICATORS

In the absence of perfect knowledge on fire effects, biological indicators (bio-indicators), or vital attributes can be used to determine the most appropriate fire regime to apply to maintain a desired ecosystem. Bio-indicators include:

- Post-fire biomass accumulation rates
- Post-fire regeneration strategies of plants within a community
- Juvenile period (time to flowering after fire) and seed bank dynamics
- Habitat requirements, reproductive biology, and post-fire response patterns of vertebrate and invertebrate fauna, especially taxa recognised as endangered

Conservative fire regimes should be designed around the requirements of the most fire-sensitive taxa, based on known fire response or inferred from vital attributes. These are plants with thin bark, obligate seeders, those that store seed in the canopy (no soil store), and which have a long juvenile period, and animals which have specialised habitat (food and shelter) requirements, long juvenile period, low reproductive capacity, and restricted distribution (especially if coupled with low mobility). A national distributional database of the post-fire regeneration strategies and flowering phenology (vital attributes) of plants should be developed for fire-vulnerable ecosystems. Voucher specimens should lodged with a national herbarium. A similar database of vital attributes and post-fire response should be developed for fire-vulnerable fauna.

6.4 MONITORING THE EFFECTS OF FIRE ON VEGETATION AND INVERTEBRATES

Monitoring, or repeated observations or measurements to assess and regulate an action, is fundamental to good management. The outcome should be feedback to influence management actions. Its objective when applied to fire research should be to assess what operational measures should be designed to avoid or to ameliorate harmful impacts on the environment. Managers must have some control over the processes which influence positive or negative ecosystem responses if monitoring is to influence management actions. To monitor for the sake of monitoring may be interesting, but it is a poor use of limited resources.

What to monitor, where, and how often, are not obvious. It is not realistic to prescribe in detail a standard monitoring protocol for New Zealand's natural ecosystems without a reasonable scientific knowledge of these systems (therefore, what, where and how to monitor) and of the management objectives. As pointed out by Gill (1986), monitoring should be done in relation to the aims of management and these aims should be as detailed as possible. Useful contributions on monitoring in relation to fire have been made by Hopkins (1989), Gill & Nicholls (1989), and Heislers (1989).

Successful monitoring requires clear objectives, cost effective methods, and adequate resources and motivation (Heislers 1989). It is not possible to monitor everything, so selecting the key ecosystem elements and parameters is critical. Monitoring techniques for vegetation and most invertebrates are given below; in some cases, special consideration may need to be given to other invertebrates or small vertebrate species.

Monitoring vegetation changes with fire

Techniques for monitoring may be qualitative, for example ground-based photographic points or remote sensing, or quantitative, where detailed measurements are made. The scale can vary from a few square metres to thousands of hectares. Costs will vary considerably according to the techniques used and the frequency of observations. An example of system for monitoring the effects of fire on jarrah (*Eucalyptus marginata*) forest vegetation is described by Heislers (1989). The following guidelines for monitoring the effects of fire are drawn from Heislers (1989) and from my experience in Western Australian ecosystems, with appropriate New Zealand references added.

- Select representative sites, ecosystems or habitats of special conservation significance for monitoring.
- Describe and document features of the site such as geomorphology and vegetation type.
- Document the known management history of the site, including fire, and keep this documentation up-to-date. Where possible, obtain and maintain weather records for the area.
- Establish permanent transects or quadrats (e.g., for forests and forest margins, Allen 1993; for open vegetation, Walls 1998). The size and number at each site will depend on the level of floristic diversity and on the available resources. Species area curves will help to determine appropriate plot/sample size to capture most of the floristic diversity.
- Species composition, relative abundance of species (quantitative or qualitative), and structure of the vegetation (height, cover and vertical density from Levy rod contacts, Levy & Madden 1933) can be measured at suitable intervals. Establish photographic points in representative quadrats.
- Select indicator species for more detailed study. These may include fire-sensitive species, threatened taxa, or even invasive weeds. Measure density

and structure (height, and breast height diameter if tree species), cover, and abundance.

- For each species, record life form, regeneration strategy, age to first flowering after fire, and general reproductive status at time of assessment.
- Lodge specimens with local herbarium for positive identification, keep voucher specimen for local reference.
- Construct a database, and determine protocols for analysing the data.
- Ensure regular reporting and follow-up management actions.

Monitoring the effects of fire on invertebrates

Friend (1995) has reviewed methods for studying the effects of fire on invertebrates. Monitoring programmes in Western Australian *Eucalyptus* forests based on the recommendations of Friend (1995) are summarised below. These may need to be modified to allow for seasonality in New Zealand species (Moeed & Meads 1985). The traps may also need to be covered with bird netting to stop them filling with leaves and to give some protection from birds, such as weka (Spurr 1996). Special methods may need to be applied for some species, such as snails.

- Sites (12) ranging from recently burnt to long unburnt are sampled 4 times each year (seasonally).
- A total of 192 pitfall traps are established at 12 sites (16 traps/site).
- Each site consists of a transect of 16 pitfall traps (cups 90 mm in diameter and 110 mm deep) arranged in four groups of four. When operational (opened), traps are ¾ filled with Galt's solution (preservative) and left open for 10 days each trap session. Traps at each site are then bulked to give 4 samples/site.
- Animals are sorted to Order level initially (e.g., ants, spiders, beetles, flies, wasps, moths, and others).
- Select taxa, e.g., spiders, are sorted to morphospecies level.

Invertebrates are usually the most abundant and diverse faunal taxa within an ecosystem. Monitoring invertebrates, as described above, can create a considerable taxonomic workload. After an initial sampling, the methods may need to be modified so that the task is manageable, but meaningful.

The most appropriate and effective systems for monitoring the effects of fire and of fire exclusion on fire-prone ecosystems should be determined from a detailed review of the literature and in consultation with relevant scientist and fire managers within DOC. In addition, the above methods for researching the effects of fire on invertebrates should be investigated for application to New Zealand ecosystems.

6.5 PRESCRIBED BURNING

There have been a number of key reports produced in New Zealand which have grappled with the controversial and complex issues of the role of fire in managing flammable ecosystems such as tussock grasslands and wetlands (e.g., McKendry & O'Connor 1990, Basher *et al.* 1990, and Allen *et al.* 1995). All of these reviews stress the need for more scientific information about the role of fire in New Zealand ecosystems.

While knowledge of effects of fire is imperfect, it is generally accepted that it has an important role in the maintenance of tussock grassland, wetland and shrubland ecosystems. As stated above, fire management policy in DOC is one of fire suppression, so many of these ecosystems are being maintained in their present state, desirable or undesirable, by illegal fires or by escapes from burning off. There has been no prescribed burning on DOC lands aside from small-scale experimental fires. If fire could be excluded from these ecosystems (which is the current policy), would this be ecologically desirable? Is occasional fire in these ecosystems desirable? Is it desirable to maintain a range of successional stages within each of the major flammable ecosystems (grasslands, shrublands, wetlands)? Is it appropriate to use prescribed fire to manage the wildfire threat by managing fuel levels, especially in some tussock grasslands?

In fire-prone environments in other parts of the world, fire policies which rely entirely on fire suppression have failed, both in terms of meeting wildfire protection objectives and biodiversity conservation objectives. For example, in parts of North America, the paradigm is shifting from fire suppression to prescribed fire. A suppression policy may be politically expedient, because interventionist management, such as prescribed fire, can be controversial. Prior to the arrival of humans, New Zealand was not as fire-prone as parts of Australia or North America, but with their arrival, many fire-prone ecosystems have been created. The fire suppression policy is reasonably effective, the mean fire size being in the order of 13 ha. However, there is a contradiction in this policy. On the one hand it is well recognised that many ecosystems are fire-induced, but on the other, all fires are suppressed and there is no use of prescribed fire to provide successional diversity.

Currently, the introduction of fire to parts of these ecosystems is unplanned. This is highly undesirable, from both a wildfire control and conservation perspective. If the fire management objectives are to control the size and impact (on commercial and conservation values) of wildfires, and to maintain some vegetation types at different successional stages, then DOC must consider the introduction of prescribed fire as a management tool to achieve them.

For example, a patch-burn strategy in which patches of the landscape are deliberately burnt under controlled conditions and at ecologically sustainable intervals may be appropriate in expanses of tussock grassland, particularly in eastern parts of the South Island. The objectives of this strategy would be to (a) assist with wildfire control by breaking up the run of major fires, (b) maintain tussock grasslands and (c) provide for successional diversity within tussock grasslands.

Depending on the values at risk, access and other constraints, the managed fire frequency on tussock grasslands could vary from 10 to 30 years, with fire excluded from nominated reference areas. Knowledge of fire behaviour and rate of fuel accumulation is needed to assist with decisions about frequency and scale of burning. Scale and patchiness would also depend on physical features, existing firebreak access, grazing pressure, but could vary from 200 to 1000 ha.

Managers must make decisions and take action with imperfect knowledge. Scientists must be willing to offer 'best bet' policy options based on existing knowledge. In the absence of perfect knowledge or detailed information, fire management can be guided by basic principles determined from the historical role of fire, the fire environment, and biological indicators of fire effects. The most appropriate fire regimes can be determined and refined as more information becomes available from research and monitoring programmes.

7. Conclusions

Until more information becomes available, the fire management policy on land administered by DOC could be based on the following principles:

- Climatic, edaphic, and biological indicators suggest that New Zealand's fire environment could be rated as low to moderate, compared with other bioregions of the world. However, remnant native forests, especially beech forests, are highly sensitive to fire and can be readily converted to a primary succession state by fire.
- Since human settlement, fire has been an important factor in creating and maintaining many ecosystems, including tussock grasslands, wetlands and shrublands, usually at the expense of native forests.
- Intense wildfires which threaten human life and property and conservation values have occurred and will continue to occur in these flammable vegetation types and often in difficult terrain. Almost all wildfires are caused by humans and are either arson, carelessness, or escapes from burning off.
- Inappropriate fire regimes in flammable vegetation types can cause undesirable ecological effects in these types and threaten fire-sensitive remnant old-growth forests.
- Prescribed fire can be used in certain ecosystems to (a) reduce the negative impacts of wildfires by managing fuel buildup and (b) maintain and enhance successional diversity.
- An ongoing fire ecology research and monitoring programme will provide the necessary information about the role of fire in natural ecosystems.

A systematic wildfire risk analysis for New Zealand should be given a high priority. This will provide a framework to analyse the best information on all significant factors likely to contribute to the wildfire threat and allow for an evaluation of alternative hazard mitigation strategies. The values at risk include human life and property and conservation values.

An outcome of this process is a map showing varying degrees of risk posed by wildfire to these values. This can be used to determine appropriate pre-suppression and suppression actions and to prioritise resource allocations. For example, in zones where the wildfire risk is identified as high, management action may be to reduce the risk by (a) increased surveillance, (b) fuel reduction or modification, including prescribed burning, or (c) immediate and full suppression action, etc. On the other hand, where the risk to people, property or conservation values is low, expenditure on pre-suppression or suppression may not be warranted and wildfires may be allowed to burn.

Fire management issues need to be incorporated into each level of land management planning and to be broadened to include fire ecology. Each Conservation Management Strategy (CMS) could include more details to guide fire management including a Conservancy Wildfire Threat Analysis, fire management objectives and strategies for special areas (ecological and economical). There is a need for another, more detailed, level of planning which addresses fire management specific to land management units such as major (or significant) protected areas. These local fire management plans should integrate all available information to identify fire issues and provide clearly defined fire management and fire research objectives and prescriptions.

The Department's reluctance to use fire as a management tool in relation to conservation of flammable vegetation types, and political and agency disagreement over the primary objective and best course of action or confusion about fire management could lead to a major fire crisis, causing damage to property and conservation values and possibly loss of human life. Fire agencies not only have a responsibility to protect the lives and property of the community at large, but also the lives of firefighters. Recognition and definition of fire issues, the formulation of clear fire management policies and objectives underpinned by sound science, and a well trained and well equipped firefighting force will reduce the risk and impact of a major fire.

8. Recommendations

1. That a comprehensive and systematic national wildfire risk analysis be undertaken to quantify the risk posed by wildfire to human life and property and nature conservation values in New Zealand.
2. That DOC, in collaboration with other rural fire authorities, develop "fuel accumulation" models for major flammable vegetation types.
3. That a national fire research working group be established in New Zealand to promote fire science, to identify gaps in knowledge and opportunities for collaboration, to exchange ideas, to disseminate information, to integrate research activities and to attract fire research funding.
4. That DOC employ a fire ecologist to develop and implement the Department's fire research plan, to develop internal and external linkages, and to provide scientific advice to DOC managers on fire issues.
5. That a national and multi-agency space-for-time investigation of the impacts of fire on native communities, species and processes be undertaken soon.
6. That a GIS database be assembled containing information about the important fire-induced vegetation types, *viz.*, wetland, tussock grassland and shrubland, and fire-vulnerable ecosystems, including location (a map), special site features, and management history (including fire). This database should include vital attributes and post-fire responses of plants and significant fauna.
7. That the most appropriate systems for monitoring the effects of fire and of fire exclusion on both vegetation and invertebrates in fire-prone ecosystems be adapted for use in New Zealand.
8. That DOC consider the strategic introduction of prescribed fire to assist with the control of wildfires and to maintain some ecosystems (especially tussock grasslands).

9. Acknowledgments

I am grateful to DOC and CALM for allowing me the opportunity to visit New Zealand and to carry out this review. I thank Kerry and Raewyn Hilliard and Susan Timmins (DOC) for their hospitality and stimulating discussions during my visit to New Zealand. Susan provided valuable comment on an earlier draft of this report. I also thank the numerous DOC people I met throughout New Zealand for their friendship, hospitality and willingness to discuss conservation and fire management. I particularly thank Dave and Gwen White for their hospitality while I was in Dunedin.

10. References

Allen, R.B. 1993. A permanent plot method for monitoring changes in indigenous forests. Unpublished report, Manaaki Whenua-Landcare Research, Lincoln.

Allen, R.B.; Basher, L.R.; Comrie, J. 1995. The use of fire for conservation management in New Zealand. Unpublished report, Manaaki Whenua-Landcare Research, Lincoln.

Alexander, M.E.; Pearce, H.G. 1992. Guidelines for investigation and Documentation of wildfires in exotic pine plantations. Draft report prepared for the meeting of Australian Forestry Council Research Working Group No. 6—Fire Management, December 9, 1992, Creswick, Victoria, Australia.

Basher, L.R.; Meurk, C.D.; Tate K.R. 1987. The effects of burning on soil properties and vegetation. New Zealand Department of Scientific and Industrial Research. *Land Resources Technical Record 18.*

Bell, D.T.; Koch, J.M. 1980. Post-fire succession in the northern jarrah forest of Western Australia. *Australian Journal of Ecology 5*: 9-14.

Burrows, N.D. 1987. The soil dryness index for use in fire control in Western Australia. *Technical Report No. 17*. Department of Conservation and Land Management, Western Australia.

Calder, J.A.; Wilson, J.B.; Mark, A.F.; Ward, G. 1992. Fire, succession and reserve management in a New Zealand snow tussock grassland. *Biological Conservation 62*: 34-45.

Clarkson, B.R. 1997. Vegetation recovery following fire in two Waikato peatlands at Whangamarino and Moanatuatua, New Zealand. *New Zealand Journal of Botany 35*: 167-179.

Clarkson, B.R.; Stanway, E.A. 1994. Vegetation recovery following fire in the Whangamarino wetland. *Science & Research Series No.73*. Department of Conservation, Wellington.

Daly, G.T. 1977. The grasslands of New Zealand. Pp. 1-40 in Langer, R.H.M. (Ed.) Pastures and pasture plants. A.H. and A.W. Reed, Wellington.

Department of Conservation 1996. Conservation action. Department of Conservation achievements and plans. Department of Conservation, Wellington.

Dickson, K.J.M.; Mark, A.F.; Lee, W.G. 1992. Long-term monitoring of non-forest communities for biological conservation. *New Zealand Journal of Botany 30*: 163-179.

Fogarty, L.G. 1994. The Karori rural/urban interface fires: associated burning conditions and fire control strategies. Proceedings, Forest and Rural Fire Association of New Zealand (FRFANZ) 4th Annual Conference, 3-5 August 1994, Rotorua, New Zealand.

Friend, G.R. 1995. Fire and invertebrates—a review of research methodology and the predictability of post-fire response patterns. *CALMScience Supplement 4*: 165-173.

Gill, A.M. 1986. Research for fire management of Western Australian State Forests and Conservation Reserves. Department of Conservation and Land Management, Western Australia.

Gill, A.M.; Nicholls, A.O. 1989. Monitoring fire-prone flora for nature conservation. Pp. 137-152 in Burrows, N.; McCaw, W.L.; Friend, G. (Eds) Fire management on Nature Conservation Lands. Proceedings of a National Workshop, Busselton, Western Australia. *Department of Conservation and Land Management Occasional paper 1/89.*

Heislers, A. 1989. Monitoring the effects of fire management on nature conservation values. Pp. 153-158 in Burrows, N.; McCaw, W.L.; Friend, G. (Eds). Fire management on Nature Conservation Lands. Proceedings of a National Workshop, Busselton, Western Australia. *Department of Conservation and Land Management Occasional paper 1/89.*

Hilliard, K. 1997. Briefing: Fire control management responsibilities, Department of Conservation. Department of Conservation, Wellington.

Hopkins, A.J.M. 1989. Monitoring for fire management in natural areas in Western Australia. Pp. 133–136 in Burrows, N.; McCaw, W.L.; Friend, G. (Eds) Fire management on Nature Conservation Lands. Proceedings of a National Workshop, Busselton, Western Australia. *Department of Conservation and Land Management Occasional paper 1/89*.

Levy, E.B.; Madden, E.A. 1933. The point method of pasture analysis. New Zealand *Journal of Agriculture 46*: 267–279.

Mark, A.F.; Smith, P.M.F. 1975. A lowland vegetation sequence in South Westland: pakihi bog to lowland mixed beech-podocarp forest. Part 1: The principal strata. *Proceedings of the New Zealand Ecological Society 22*: 76–92.

Masters, S.E.; Holloway, J.T.; McKelvey, P.J. 1957. The national forest survey of New Zealand, 1955. Vol 1. The indigenous forest resource of New Zealand. Government Printer, Wellington.

Maunder, W.J. 1971. Elements of New Zealand's climate. Pp. 229–261 in Gentilli, J. (Ed.) World survey of climatology: Climates of Australia and New Zealand. Elsevier, Amsterdam.

McGlone, M.S. 1983. Polynesian deforestation of New Zealand: a preliminary synthesis. *Archaeology in Oceania 18*: 11–25.

McGlone, M.S. 1989. The Polynesian settlement of New Zealand in relation to environmental and biotic changes. *New Zealand Journal of Ecology 12* (supplement): 115–129.

McKendry, P.J.; O'Connor, K.F. 1990. The ecology of tussock grasslands for production and protection. Centre for Resource Management, Lincoln University.

Moeed, A.; Meads, M.J. 1985. Seasonality of pitfall trapped invertebrates in three types of native forest, Orongorongo Valley, New Zealand. *New Zealand Journal of Zoology 12*: 17–53.

Mount, A.B. 1972. The derivation and testing of a soil dryness index using run-off data. *Tasmanian Forests Commission Bulletin No.4*.

Parliamentary Commissioner for the Environment 1995. A review of the Government system for managing the South Island tussock grasslands: With particular reference to tussock burning. Wellington.

Pearce, G. 1996. An initial assessment of fire danger in New Zealand's climatic regions. *Fire Technology Transfer Note No.10*. New Zealand Forest Research Institute, Rotorua.

Rogers, G.M.; Leathwick, J.R. 1994. North Island seral tussock grasslands 2. Autogenic succession: change of tussock grassland to shrubland, *New Zealand Journal of Botany* 32: 287–303.

Spurr, E.B. 1996. Environmental effects of rodent Talon® baiting. Part 2. Impacts on invertebrate populations. *Science for conservation 38*: 12–27.

Timmins, S.M. 1992. Wetland vegetation recovery after fire. Eweburn Bog, Te Anau, New Zealand. *New Zealand Journal of Botany 30*: 383–399.

Wardle, P. 1991. Vegetation of New Zealand. Cambridge University Press, Cambridge.

Williams, P.A.; Courtney, S.; Hall, G.; Mew, G. 1990. Pakihi and surrounding vegetation in North Westland, South Island. *Journal of the Royal Society of New Zealand 20*: 179–203.

Working Party on Sustainable Land Management 1994. South Island High Country Review. Final report from the Working Party on Sustainable Land Management.