REVIEW

Frequency and impact of Holocene fire in eastern South Island, New Zealand

Geoffrey M. Rogers[1]*, Susan Walker[2], Les M. Basher[3] and William G. Lee[2]
[1]Research, Development, and Improvement Division, Department of Conservation, PO Box 5244, Dunedin 9016
[2]Landcare Research, Private Bag 1930, Dunedin 9016
[3]Landcare Research, Private Bag 6, Nelson 7042
*Author for correspondence (Email: grogers@doc.govt.nz)

Published on-line: 3 December 2007

Abstract: Our evaluation of pre-settlement Holocene (10 000–1000 BP) fire, using radiocarbon-dated charcoals and pollen and charcoal spectra in pollen diagrams, concludes that fires were infrequent and patchy in the eastern South Island of New Zealand. Charcoal radiocarbon dates point to three broad phases of fire frequency: infrequent patchy fires from 10 000 to 2600 BP; a slightly increased frequency between 2600 and 1000 BP; and an unprecedented increase of fires after 1000 BP, which peaked between 800 and 500 BP. We suggest that natural fire was driven more by vegetation flammability (with ignitibility and combustibility components) than climate within this rain-shadow region, that plant chemistry principally determined fire frequency, and that topography determined the extent of fire. The review suggests that there were rare spatial and temporal instances of a feedback relationship between fire and early-successional grasses in eastern South Island. This occurred only within narrow-range, cool environments, whose equilibrium communities were of flammable, phenolic-rich woody species and grasses, and was predominantly in the late pre-settlement period. Elsewhere, grasses and herbs were understorey components to otherwise low-flammability, hardwood forest and scrub.

Keywords: grasslands; pollen diagrams; rain-shadow climate

Introduction

Setting restoration goals and managing eastern South Island drylands can be guided by palaeoecological insights into past physical environments, the pre-settlement pattern of vegetation, and landscape-scale disturbances such as fire. Knowledge of how present landscapes have departed from those of pre-settlement times allows measurement of the achievability of restoration goals from present vegetation patterns. The post-settlement fire regime is thought to have differed substantially from the natural or pre-settlement one, generating apparently unprecedented bracken (*Pteridium esculentum*), scrub, and grass cover (McGlone 2001). Although there is substantial evidence for natural fire in eastern South Island (Molloy et al. 1963; Ogden et al. 1998; McGlone 2001), it is difficult to determine its frequency and extent (Burrows 1996; McGlone & Moar 1998), or the consequences for vegetation pattern. Opinions differ as to the influences of rain-shadow climates and fire on the extent and pattern of pre-settlement grassland.

From radiocarbon-dated charcoal, Ogden et al. (1998) found evidence of pre-settlement fires occurring at least every few centuries with a fire return time at any one place of one to two millennia. Burned areas usually succeeded to forest before the next fire. In a review of the effects of natural fire in south-eastern South Island, McGlone (2001) noted that only some bogs record local as opposed to distant fires, that *Phyllocladus* had been widely fire-suppressed (Kawarau Gorge, Mackenzie Basin, and the Arrowsmith Range), and that grass became common during a period of higher fire frequency at only a few sites. McGlone's schematic map for pre-settlement times shows low-forest–scrub–grassland for the dry interior of Otago and southern Canterbury. McGlone et al. (1997) believe that despite fire-induced scrub and grassland being present throughout the

Holocene, permanent, large-scale destruction of Central Otago's forests by fire occurred only after Polynesian settlement. In Otago's Upper Clutha district, Wardle (2001, p. 540) pictures extensive podocarp forest and scrub with less but increasing *Nothofagus* forest in the late Holocene 'that was able to recover from the intermittent fires of the pre-human era'.

On the other hand, after monitoring a tussock grassland for 30 years in humid, montane east Otago, Mark and Dickinson (2003, p. 655) 'question the interpretation of a general lack of tussock grassland below treeline in immediate pre-human times, and its widespread downslope replacement of forest following Polynesian fires' and claim 'the evidence is at variance with the known ecology of the dominant grass species, evidence from relevant pollen records, and results from their study'. Further, after examining the pattern of serotiny in *Leptospermum scoparium*, Bond et al. (2004, p. 124) suggested 'in the drier parts of the South Island rainshadow region there likely would have been mosaics of fire-maintained grasslands and shrublands with more or less extensive forest patches surviving in relatively protected areas'.

By reviewing the evidence for fire and associated seral grassland from published palaeoecological data, we sought to provide a fuller picture of Holocene fire and vegetation history in eastern South Island than has hitherto been assembled. Specifically, we asked whether there is evidence for fire-maintained *Pteridium*-fernland and grassland in the pre-settlement period.

Figure 1. Distribution of pollen diagrams used to assess occurrence of local, natural fire and associated seral grassland in eastern South Island.

Methods

Incidence of fire

We examined the frequency and pattern of fire, both pre- and post-settlement, using 234 radiocarbon-dated charcoals (conventional ages) (115 pre- and 119 post-settlement) extracted from mineral soil and peat bogs. A list of 169 dates to 1992 (Ogden et al. 1998) was updated to December 2003 to 234 using further records from the University of Waikato's Radiocarbon Dating Laboratory (A. Hogg, pers. comm.) and the Institute of Geological and Nuclear Sciences' Rafter Radiocarbon Laboratory (D. Chambers, pers. comm.). The list applies to the four regions of eastern South Island: Marlborough, Canterbury, Otago, and Southland. A frequency distribution of dates per 100-year interval was used to assess fire frequency. Only the broadest limits can be imposed on perceived fire-phases because date precision is compromised by the inbuilt age of wood at its incineration and possible post-depositional contamination of its original carbon content. Climatic influence on the distribution of fire was assessed by spatially comparing water-deficit zones (standardised for area) with radiocarbon-dated charcoal in the pre- and post-settlement periods using the climate data of Leathwick et al. (2003).

Intervals of recurrent fire at any one place were assessed from the seven sites where stratigraphically intact, sequentially accumulated, and dated charcoal lenses from soils or peat of the pre-settlement period are available.

To examine the hypothesis that vegetation flammability contributed to the pattern of natural fire, we compiled frequency data of the combusted species identified from radiocarbon-dated charcoal.

Extent of grasses and grassland

We reviewed 35 published pollen diagrams (Table 1; Fig. 1) from Marlborough, Canterbury, and Otago, the most fire-prone, rain-shadow region of the South Island, to address three questions:

Is there evidence for local (as opposed to distant) natural fires?

Is there evidence of a fire-induced spread or maintenance of grassland in pre-settlement times?

What was the magnitude of change in grasses between pre- and post-settlement times?

Charcoal spectra from peat cores were used to address the first question. Charcoal spectra are useful data for the purpose of understanding local fire histories but need to be interpreted with caution (McGlone 2001) for the following reasons: palynologists have not analysed charcoal consistently; not all cores capture charcoal evidence of local fires; and the sources of peat bog charcoal vary widely. Topogenous or depression

Table 1. Geographic and temporal characteristics of Poaceae pollen and charcoal from Holocene pollen diagrams from eastern South Island. Some diagrams differentiate between large-grained (Chionochloa) and small-grained Poaceae pollen, whereas the remainder record undifferentiated Poaceae pollen. na, not applicable; undiff., undifferentiated.

Site	Grid reference (NZMS 260) and (altitude)	Age range (BP)	Landform	Evidence from charcoal spectrum of pre-settlement fire	Concordance in pre-settlement peaks of poaceae pollen and charcoal	Type of Poaceae pollen	Estimated pre-settlement Poaceae pollen (%)	Estimated post-settlement Poaceae pollen (%)	Times increase	Estimated pre-settlement *Pteridium* (%)	Estimated maximum post-settlement *Pteridium* (%)	Reference
Inland Kaikoura Range												
Winterton Bog 1	O30/536083 (1480 m)	>6000 to present	hill-slope greywacke mountain	no	no	Undifff.	2	48	24	1	27	McGlone & Basher 1995
Winterton Bog 2	O30/536083 (1480 m)	>6000 to present	hill-slope greywacke mountain	no	no	Undiff.	5	65	13	0	48	McGlone & Basher 1995
Andy's Gully	O30/458085 (810 m)	mid-Holocene	hill-slope greywacke mountain	yes; abundant charcoal fragments; not dated	na	Undiff.	3 (mean of three spot samples)					McGlone & Basher 1995
Nth Canterbury floodplain												
Pyramid Valley Swamp	M33/772037 (330 m)	early Holocene to present	floodplain	Na	na	Undiff.	2	c. 50	c. 25			Moar 1970
Canterbury Plains												
Christchurch city	M35/810410 (10 m)	spot samples 7000–2000	floodplain	na	na	undiff.	9.7 (mean of three spot samples)					Moar 1971
Timaru Downs, Timaru	J39/698406 (30 m)	7000–1000	floodplain	Na	na	Undiff.	4					Moar 1971
Swinton Park Farm, Amberley	M34/871853 (30 m)	mid-to late Holocene	intermontane basin/ valley	Na	na	Undiff.	3					Moar 1971
Travis Swamp	M35/847468 (5 m)	1600–750	floodplain	no	no	large small	2 2	6 48	3 24	2	68	McGlone 1995 unpubl
Cass Basin												
Woolshed Hill	K33/077020 (1000 m)	mid-to late Holocene	hill-slope greywacke mountain	Na	na	Undiff.	3					Moar 1971
Mt Horrible	K34/065974 (600 m)	late glacial to mid-to late Holocene	hill-slope greywacke mountain	Na	na	Undiff.	2					Moar 1971
Lake Hawdon	L34/162885 (600 m)	mid-Holocene to late Maori era	intermontane basin/ valley	Na	na	Undiff.	1	15	15	0	8	Moar 1971
Kettlehole Bog	L34/113938 (600 m)	late glacial to present	intermontane basin/ valley	Na	na	Undiff.	5	40	9			Lintott & Burrows 1973
Kettlehole Bog	L34/113938 (600 m)	late glacial to 700	intermontane basin/ valley	late glacial fire(s), 13 600–11 500 BP	yes, late glacial only	undiff.	1	8	8			McGlone et al. 2004
Rakaia River												
Lake Henrietta	K34/877744 (600 m)	11 700 to late pre-settlement	intermontane basin/ valley	Na	na	Undiff.	2					Moar 1973
Mackenzie Basin												
Duncan Stream	H38/755764 (900 m)	8000 to present	intermontane basin/ valley	yes, two fires in 5500–4000 BP and one in 4000–1200 BP	yes, post-5000 BP rise in charcoal and Poaceae	large small	1–5 2–10	5 30	1 3	1	2	McGlone & Moar 1998
Ben Dhu Scientific Reserve	H39/615392 (600 m)	800 to present	intermontane basin/ valley	na	na	Undiff.		60			3	McGlone & Moar 1998

Site	Grid reference (NZMS 260) and (altitude)	Age range (BP)	Landform	Evidence from charcoal spectrum of pre-settlement fire	Concordance in pre-settlement peaks of poaceae pollen and charcoal	Type of Poaceae pollen	Estimated pre-settlement Poaceae pollen (%)	Estimated post-settlement Poaceae pollen (%)	Times increase	Estimated pre-settlement *Pteridium* (%)	Estimated maximum post-settlement *Pteridium* (%)	Reference
Ben Ohau Range, South Canterbury												
Twin Stream, Tasman Valley	H37/747955 (1036 m)	late Holocene to present	hill-slope greywacke mountain	yes, one fire at 1115 BP	na	undiff. spot samples	3 (mean of two samples)	25.7 (mean of three samples)	8.6			Archer 1979
Arrowsmith Range												
Quagmire Tarn, Prospect Hill	J35/576633 (740 m)	12 000 to present	hill-slope greywacke mountain	na	na	undiff.	1 (with peaks of 8)		35	35		Burrows & Russell 1990
Windy Tarn	J35/567650 (750 m)	early Aranuian to present	hill-slope greywacke mountain	na	na	undiff.	1–6	65	10.8			Burrows & Russell 1990
North Otago												
Pleasant River	J43/318137 (5 m)	3840 to present	floodplain	possibly 1 basal fire c. 3800 BP	no	undiff.	2.5	48	19	1	46	McGlone 2001
East Otago												
Glendu, Waipori River	H44/580810 (500 m)	12 000 to present	montane peneplain	yes, three peaks c. 4000–3722 BP and one c. 1100 BP	no Poaceae response to charcoal-evidence for fire	large small	1.5 3	15 42	10 14	2	50	McGlone & Wilmhurst 1999a
Clark's Junction	H44/852950 (520 m)	late Holocene to present	montane peneplain	no	no	large small	7 12	17 57	2.4 4.8	2	34	Leslie & McGlone 1973; McGlone 2001
Teviot Swamp, Lammerlaw Range	G43/488026 (980 m)	late Holocene to present	montane peneplain	no but short pre-settlement period	no	large small	1 1	10 38	10 38	1	37	McGlone 2001
Swampy Hill	I44/139868 (740 m)	12 000 –3000	montane peneplain	na	na	undiff.	4					McIntyre & McKellar 1970
Central Otago												
Idaburn Valley	H41/509619 (420 m)	7500–4000; 800 to present	intermontane basin/ valley	no	no	undiff.	6–15	47	3.1	2	15	McGlone & Moar 1998; McGlone 2001
Earnscleugh Cave	G42/190387 (540 m)	2176 to present	hill-slope block mountain	no	no	undiff.	4	45	11.3	1	6	Clark et al. 1996
Kawarau Gorge	F41/026711 (800 m)	9500 to late Holocene	hill-slope block mountain	yes, five in 12 000 years	yes, two; one early and one late Holocene	undiff.	2–20					McGlone et al. 1995
Islands I, Garvie Mountains	F43/864196 (1460 m)	9600 to present	crest of block mountain	yes, three in c. 7000 years	yes, two; one mid and one late Holocene	undiff.	5	45	9	0	42	McGlone et al. 1995
Islands II, Garvie Mountains	F43/868196 (1450 m)	early Holocene to present	crest of block mountain	yes, four in c. 7000 years	yes, three mid to late Holocene	undiff.	3	50	16.7	0	22	McGlone et al. 1995
Campbell Creek, Old Man Range	G43/108236 (1200 m)	8000 to present	crest of block mountain	no macroscopic charcoal but high microscopic amounts c. 7700 BP	one, early Holocene	large small	3 6-17	12 33	4 4.7	1	28	McGlone et al. 1997
Ruined Hut 1, Old Man Range	G43/131224 (1410 m)	7000 to present	crest of block mountain	no macroscopic charcoal	no	large small	2 11	13 55	6.5 5	1	12	McGlone et al. 1997
Ruined Hut 2, Old Man Range	G43/131228 (1410 m)	1500 to present	crest of block mountain	no macroscopic charcoal	no	large small	1 10	8 22	8 2.2	0	6	McGlone et al. 1997

Site	Grid reference (NZMS 260) and (altitude)	Age range (BP)	Landform	Evidence from charcoal spectrum of pre-settlement fire	Concordance in pre-settlement peaks of poaceae pollen and charcoal	Type of Poaceae pollen	Estimated pre-settlement Poaceae pollen (%)	Estimated post-settlement Poaceae pollen (%)	Times increase	Estimated pre-settlement *Pteridium* (%)	Estimated maximum post-settlement *Pteridium* (%)	Reference
Hyde Cirque, Old Man Range	G43/124289 (1520 m)	7500 to present	crest of block mountain	no macroscopic charcoal	no	large small	1 6	8 16	8 2.7	1	13	McGlone et al. 1997
Potters Bog, western Old Man Range	F43/082240 (1200 m)	late Holocene to present	no, but short pre-settlement period	crest of block mountain	no	large small	1 6	12 46	12 7.7	1	36	McGlone 2001
Pomahaka Rd, eastern Old Man Range	G43/131224 (875 m)	late Holocene to present	hill-slope block mountain	no macroscopic charcoal	no	large small	1 4	15 60	15 15	1	4	McGlone 2001

bogs and lakes are vulnerable to continued inwash of catchment-derived charcoal long after a local fire, perhaps providing more than one stratigraphic lens (McGlone et al. 1984). Charcoal in ombrogenous or blanket peats and dome peats is generally derived in situ. Further, peat bog charcoal has both microscopic and macroscopic particle sizes, the former at a more or less constant background amount and mostly aolian in origin, perhaps from as far afield as Australia; the latter mostly as lenses, probably locally derived, providing more reliable evidence for local fires. Despite its source variability, careful interpretation of peat bog charcoal as an adjunct to pollen profiles gives a useful insight into landscape history. Accordingly, we looked at the frequency and timing of peaks of larger particle charcoal in charcoal spectra as opposed to background amounts of fine airborne particles to provide evidence of local as opposed to distant fires.

Evidence of a fire-induced spread of grasses in pre-settlement times was investigated by looking for concordance between the peaks of charcoal and Poaceae pollen in pollen diagrams. Frequencies of pre-settlement Poaceae pollen commonly have little variability about a mean value, perhaps with irregular, temporary peaks that return again to base levels. Poaceae pollen from peat bogs is sometimes reported in two categories enabling comparisons of its large- and small-grained components. Large-grained Poaceae pollen is mainly derived from tall (*Chionochloa*) tussocks. Modern pollen rain studies indicate a conservative presence of *Chionochloa* in the pollen record, perhaps partly due to their masting behaviour and poor dispersal (McGlone 2001). Small grains are sourced from all the other grass genera, including short tussocks of *Festuca*, *Poa*, and *Rytidosperma* in a range of environments; *Dichelachne*, *Elymus*, *Puccinellia*, *Deyeuxia*, *Microlaena*, and *Rytidosperma* in semi-arid environments; and *Poa*, *Agrostis*, *Microlaena*, and *Trisetum* prominent above the treeline.

The scale of human-induced change in the extent of grassland was examined by comparing the percentage frequency of Poaceae pollen in diagrams spanning both the pre- and post-settlement periods. Our intention here was to extrapolate from the present relationship between Poaceae pollen and the extent of grassland to that of the pre-settlement period across landform classes. We also computed a correlation coefficient between present and past percentages of Poaceae pollen for all pollen diagrams to test whether grassland expansion is linked to its pre-settlement extent. However, cautious interpretation of these data is necessary because pollen frequencies are relative and very much a function of the entire contributing flora. Accordingly, the relative frequencies of plants of open vegetation will increase with loss of trees and shrubs as a result of post-settlement fire. We also note that the amounts of uppermost Poaceae pollen in pollen diagrams are swelled by pollen from exotic grasses.

Finally, we used pollen diagrams to estimate the pre- and post-settlement percentages of *Pteridium* spores as a further strong indicator of changes in fire-dependent seral vegetation.

Results

Charcoal evidence for fire

The frequency distribution of the 234 radiocarbon-dated charcoals, which may be biased toward younger dates (Ogden et al. 1998), suggested three phases of fire frequency (Fig. 2):

From c. 10 000 BP to 2600 BP, sporadic dates of one per 114 years (cf. 1:192 of Ogden et al. 1998) point to few and irregular fires. There is no convincing evidence of changes in fire frequency – small peaks are often interspersed with several centuries of no dates.

From 2600 BP to c. 1000 BP, increased dates of

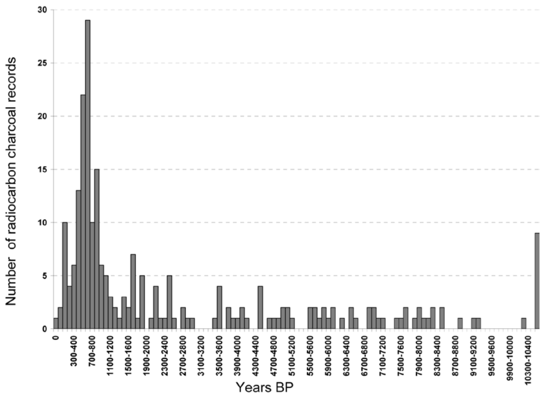

Figure 2. Frequency distribution with 100-year intervals of radiocarbon-dated (yr BP) charcoal from eastern South Island. The right-hand histogram bar represents all dates >10 500 BP.

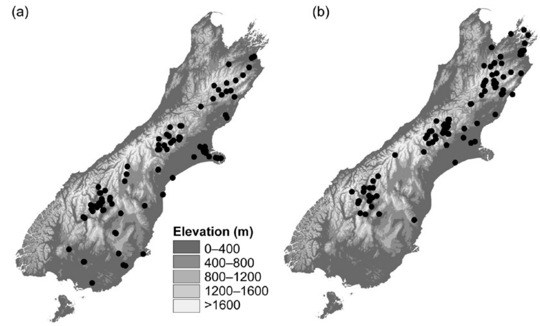

Figure 3. Distribution of radiocarbon-dated charcoal across elevation zones of eastern South Island: (a) >1000 BP (pre-settlement); (b) <1000 BP (post-settlement).

one per 34 years (cf. 1:50 of Ogden et al. 1998) suggest a possible small increase in fire frequency.

There is a big increase in dates from 1000 BP onwards (one per 9 years), which peak between 800 BP and 500 BP (see also McGlone et al. 1994; Ogden et al. 1998).

The few dates >10 000 BP result from erosion-censoring of the record and/or little forest in the last glacial or early Holocene landscape.

The geographical distributions we mapped of pre- and post-settlement radiocarbon dates from charcoal were broadly similar (Fig. 3). The distributions are biased toward the hill and mountain topography of Marlborough, western Canterbury, and Central and West Otago. Within these regions, several clusters probably reflect intensive search effort in studies of landscape history, particularly in the Clutha River headwaters in Otago (Wardle 2001), the headwaters of the Waimakariri, Rakaia, and Rangitata rivers of inland Canterbury (Burrows 1983, 1996), the environs of Christchurch City (Molloy 1995), and Molesworth Station and Wairau Plains in Marlborough (Basher et al. 1995; McGlone & Basher 1995). Nevertheless, we found some differences in the pattern of pre- and post-settlement dates: the Marlborough Sounds have many more post-settlement dates, perhaps reflecting few natural fires; Banks Peninsula has no post-settlement dates – the abundant cover of forest in early European times (Johnston 1961) suggests few Maori-lit fires; there are many more pre-settlement dates in south Canterbury and Southland.

Is there a bias in dated charcoals across a rainfall gradient or specifically across water-deficit zones (standardised for area) for the pre- and post-settlement periods? The greatest concentration of both pre-and post-settlement dates is from the drier end of the water-deficit spectrum, although there are no post-settlement dates from the driest zone (Central Otago) (Fig. 4). There are more dates in the post-settlement period at the humid end of the gradient as anthropogenic fire extended to environments generally outside of the natural fire envelope.

Seven sites with sequential layers of dated charcoal provided data to assess the interval of recurrent, pre-settlement fire at any one place (Table 2). Intervals range from 300 to 4600 years, with two clusters: 650–1250 and 2000–2300 years. The data are derived from Canterbury's greywacke mountains, the Canterbury Plains near Christchurch, Mackenzie Basin peat bogs, and Otago's schist block mountains. These interval estimates are considered maxima because not all fires will produce detectible charcoal in paleosols and peat bogs, particularly if herbaceous vegetation covers the bog.

Phenolic-rich woody plants such as podocarp trees, *Phyllocladus alpinus*, and *Kunzea ericoides* are important in the frequency distribution of radiocarbon-dated charcoal (Table 3). However, low phenolic *Nothofagus* is also prominent. Tree-species' charcoal is much more frequent than shrub-species' charcoal.

What evidence is there for local as opposed to distant fires in the charcoal spectra from pollen diagrams? The three diagrams from a Marlborough site (upper montane, Inland Kaikoura Range) have background levels of charcoal during their short pre-settlement period and no evidence of local fire (Table 1; McGlone & Basher 1995). Unfortunately, only 4 of the 16 pollen diagrams from Canterbury include pre-settlement charcoal spectra. Travis Swamp north of Christchurch shows minor background levels only and no evidence

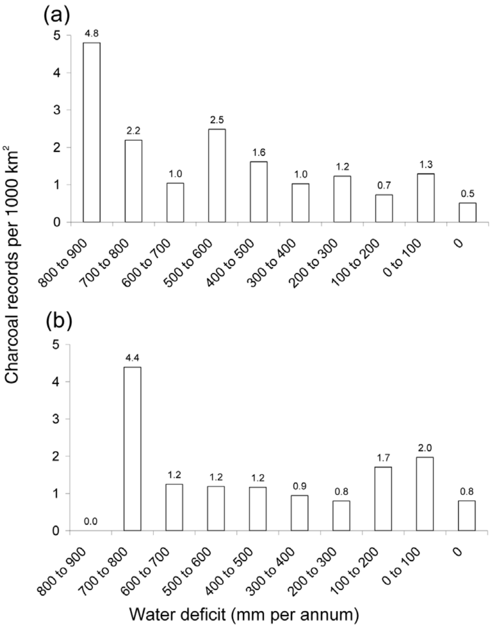

Figure 4. Distribution of radiocarbon-dated charcoals by water-deficit zone in eastern South Island, standardised for area: (a) pre-settlement; (b) post-settlement.

of local fire in a short pre-settlement period (Table 1; McGlone 1995 unpubl.). There is charcoal evidence of one or more local late-glacial fires, but no Holocene fires, in the Cass Basin of the upper Waimakariri Basin (McGlone et al. 2004). The remaining pollen diagrams are from the western Mackenzie Basin: Duncan Stream has background levels of charcoal to c. 5000 BP, then two or possibly three peaks probably corresponding to local fires (McGlone & Moar 1998); and Twin Stream has dated charcoal at c. 1115 BP (Archer 1979). These few Canterbury pollen diagrams with charcoal spectra are supplemented by several other studies reporting charcoals in soils dated to the pre-settlement era in Canterbury's erosion-prone western mountains (Molloy & Cox 1972; Burrows & Russell 1990; Burrows et al. 1993; Burrows 1996) and from the Canterbury Plains between the Waimakariri and Selwyn rivers (Cox & Mead 1963; Molloy 1995).

Fourteen of Otago's 16 pollen diagrams have charcoal spectra from the pre-settlement period. Four of those 14 have either radiocarbon-dated, macroscopic charcoal indicative of local fires or peaks in microscopic charcoal with stratigraphically inferred ages probably derived from fires within the vicinity (Table 1). Glendhu Bog, on a humid eastern Otago peneplain, has three charcoal lenses from c. 4000 to c. 3700 BP, which may relate to one fire and discontinuous inwash of charcoal, and one at c. 1100 BP (McGlone & Wilmshurst 1999a). A Kawarau Gorge site has four charcoal peaks in c. 9000 years (McGlone et al. 1995). Two profiles from the Islands I and II wetland complex on the crest of the Garvie Mountains show charcoal evidence of a fire on the lower flanks of the range at c. 2400 BP (McGlone & Meurk unpubl., reported in McGlone et al. 1995).

Fire-induced spread of grassland in pre-settlement times

Is there evidence of fire-induced grassland from a concordance in peaks of Poaceae and charcoal in pollen diagrams? Unfortunately, only three of the seven diagrams from Marlborough and Canterbury that have charcoal spectra substantially span the pre-settlement era. Neither Travis Swamp near Christchurch nor the Cass Basin has concordant peaks (Table 1). Duncan Stream in the Mackenzie Basin has a gradual, post-5000 BP rise of Poaceae in a period of two or possibly three charcoal peaks corresponding to local fires (McGlone & Moar 1998). In the absence of a charcoal spectrum, there is indirect evidence for fire disturbance at Quagmire Tarn, Rakaia River, where there is a correspondence of two small peaks of Poaceae and *Coprosma* with small troughs of *Phyllocladus* (Burrows & Russell 1990). Otago has 14 diagrams with charcoal spectra, four of which require comment. At Glendhu in east Otago, there are two distinct peaks of both large- and small-grained Poaceae coincident with charcoal peaks (McGlone & Wilmshurst 1999a). At Islands II Bog on the Garvie Mountains and at Kawarau Gorge on the Pisa Range there are coincident, mid-Holocene peaks in Poaceae and charcoal (McGlone et al 1995). At Campbell Creek on the Old Man Range, Poaceae pollen and charcoal decline throughout the mid-Holocene from greater, early Holocene amounts (McGlone et al. 1997).

Do the amounts of Poaceae pollen suggest abundant grasses or grassland in pre-settlement times that were either environmentally or fire-maintained? Most of the 20 pollen diagrams from Marlborough and Canterbury show more or less uniform and low percentages (≤5%) of Poaceae pollen in pre-settlement times (Table 1). The exceptions are (1) a spot sample of 20% from the Canterbury Plains near Christchurch (Moar 1971) and (2) at Duncan Stream, Mackenzie Basin, where both small- and large-grained pollen increased from relatively insignificant amounts after 5000 BP (1% to 5% and 2% to 10%, respectively) during a period of natural fires (McGlone & Moar 1998).

In Otago, there are two low-altitude diagrams. In the Idaburn Valley in driest Central Otago, there is no charcoal evidence of local fire, yet Poaceae pollen gradually increases to significant amounts (6% to 15%) in pre-settlement times and *Olearia* correspondingly declines. The other low-altitude diagram at Earnscleugh

Table 2. Intervals of recurrent fire at any one place as recorded in stratigraphically intact, sequentially accumulated, and dated charcoal lenses from soils or peat of the pre-settlement period of the Holocene in eastern South Island. * Charcoal layers not radiocarbon dated; age estimates from peat bog or lake sediment stratigraphy.
** Treated as one event because of possibility of continuing inflow of surface charcoal to peat bog from surrounding catchment slopes. Fire date of 3722 used for interval calculation. *** Treated as one event with a midpoint age of because of overlapping dates within a single, stratigraphically conformable layer of charcoal at three closely adjacent sites

Location	Grid reference (NZMS 260)	Fire dates from charcoal (yr BP)	Fire interval (yr)	Reference
Quagmire Tarn, Arrowsmith Range	J35/576633	*3800; 3500; 2600	300; 900	Burrows & Russell 1990
Glendhu, Waipori River, East Otago	H44/ 580810	**3 between c. 4000 and 3650 with one dated at 3722 ± 73; *c. 1100	2622 (one fire interval between 3722 BP and c. 1100 BP)	McGlone & Wilmshurst 1999a
Manorburn, Central Otago	G42/497302	7667 ± 71; 5658 ± 130; 2105 ± 92; 1466 ± 107	2009; 3553; 649	L. Basher (unpubl. data)
Ashburton River, Canterbury	J35/545487	4498 ± 70; 2139 ± 65	2359	L. Basher (unpubl. data)
Porters Pass, Canterbury	K34/806710	8900 ± 110; 6900 ± 90	2000	L. Basher (unpubl. data)
Duncan Stream and Twizel Sites 1 and 2, Mackenzie Basin	H38/755764	7996 ± 93; 6814 ± 88; ***5220 ± 90 + 5170 ± 90 + 5068 ± 130 + 4825 ± 84; 3786 ± 83; 2929 ± 82	1182; 1791 (midpoint of 5023 taken of four overlapping dates); 1237; 861	McGlone & Moar 1998; L. Basher (unpubl. data)
Broadfields, Christchurch	M36/659364	6504 ± 94; 1860 ± 96	4644	Molloy 1995

Cave has low percentages of Poaceae pollen. At montane elevations, Poaceae has a variable presence on Otago's eastern, cool, humid peneplains: Clark's Junction has 7% and 12% of large- and small-grained Poaceae, respectively, whereas Swampy Hill, Teviot Swamp, and Glendhu Bog have relatively insignificant percentages. Other mid-altitude Otago sites are Kawarau Gorge, which has Poaceae increasing from 2% to a late pre-settlement peak of 20%, and Pomahaka Road, which has virtually no large grains and 4% of small-grained Poaceae. The remaining seven diagrams are from above the treeline. Of the five that differentiate *Chionochloa* pollen, all are at 1–3%, while the small grains are at slightly greater amounts, suggesting a significant presence of short tussocks and/or other non-tussock alpine grasses. The remaining two diagrams with undifferentiated Poaceae pollen have amounts in agreement with this scenario.

In summary, a basin-floor site in Central Otago shows appreciable amounts of non-*Chionochloa* grasses with no fire influence; of the seven diagrams from the eastern peneplains and mid-altitude flanks of the block mountains, two show moderate Poaceae and the remainder a low presence; and above the treeline, large

Table 3. Species frequency identified from radiocarbon-dated charcoal obtained from soil or peat of the pre-settlement period of the Holocene in eastern South Island. n = 127.

Taxa	Frequency (%)
Nothofagus spp.	30 (23.6)
Phyllocladus alpinus	27 (21.3)
Prumnopitys taxifolia	18 (14.2)
Podocapus totara / P. hallii	15 (11.8)
Kunzea ericoides	10 (7.9)
Hebe spp.	10 (7.9)
Leptospermum scoparium	5 (3.9)
Podocarpus spp.	3 (2.4)
Dacrycarpus dacrydioides	2 (1.6)
Discaria toumatou	2 (1.6)
Compositae shrub	2 (1.6)
Libocedrus bidwillii	1 (0.8)
Dracophyllum spp.	1 (0.8)
Coprosma spp.	1 (0.8)

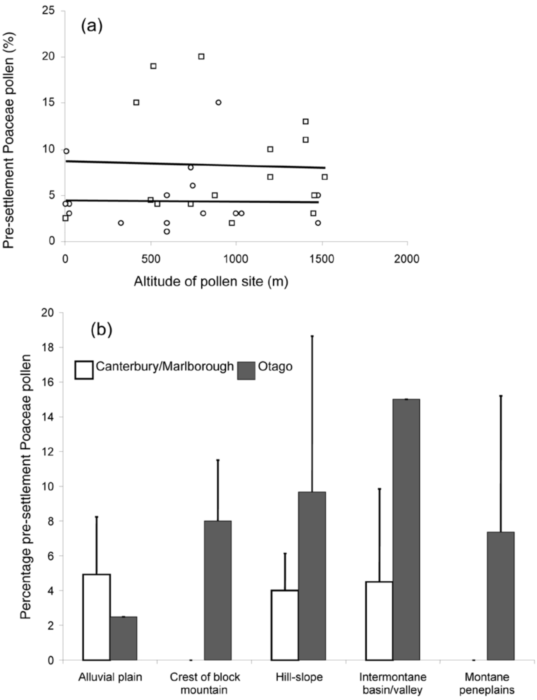

Figure 5. Relationship between percentage of pre-settlement Poaceae pollen (includes sum of small- and large-grained pollen) and (a) altitude of the pollen sample site with lines of best fit, and (b) landform class (with error bars) in Otago (open squares) and Canterbury/Marlborough (open circles) in eastern South Island, using data in Table 1.

grains are at amounts that led McGlone et al. (1997) to suggest that *Chionochloa* tussocks were possibly prominent only on the summits of the ranges (in that instance, Old Man Range). Accordingly, we found no consistent association between Poaceae in the late Holocene and altitude or landform class in Otago or Canterbury (Fig. 5). In addition, the amounts of pre-settlement Poaceae are significantly greater in Otago diagrams compared with those of Canterbury (Table 1) (Otago mean = 6.7 ± 3.7; Canterbury mean = 3.8 ± 2.7; $t_{32} = -2.38$, $P = 0.011$), especially within intermontane valleys and basins (Table 1; Fig. 5).

Change in grass pollen from pre- to post-settlement times

The majority of landform classes in Marlborough, Canterbury, and Otago showed large increases (>13-fold) in Poaceae pollen from late pre-settlement times to the present (Table 4). In Otago, the three upland landforms, block-mountain summits, hill-slopes, and montane peneplains, showed similar 13-fold increases, whereas the one intermontane-basin site (Idaburn Valley) was comparatively low at three-fold. Canterbury and Marlborough montane hill-slope sites have greater than 18-fold increases, but the intermontane-basin/valley sites are, like in Otago, much lower. The three floodplain sites in Canterbury and Otago, where the influence of pasture grasses in present percentages would be greatest, had 19-fold increases. The correlation across all 24 sites was moderately positive ($r_{22} = 0.39$). In other words, grasses have expanded in accordance with their pre-settlement presences but this varied between landforms.

Table 4. Mean increases in multiples of original percentages of Poaceae pollen from late pre-settlement to the present across regional landform classes in pollen diagrams from eastern South Island. n = number of pollen diagrams sampled.

	Differentiated Poaceae				Undifferentiated Poaceae		Combined Poaceae
	n	Large-grained	Small-grained	n		n	
Marlborough							
Hill-slope				2	18.5	2	18.5
Canterbury							
Hill-slope				2	22.9	2	22.9
Intermontane basin/valley	1	1.0	3.0	3	12.0	3	10.3
Floodplain	1	3.0	24.0	1	25.0	2	19.3
Otago							
Summit of block mountain	5	7.7	4.5	2	12.9	7	10.6
Montane peneplain	3	7.5	18.9			3	13.1
Hill-slope	1	15.0	15.0	1	11.3	2	13.2
Intermontane basin/valley				1	3.1	1	3.1
Floodplain				1	19.0	1	19.0

Is there evidence from *Pteridium* spores of fire-maintained fernland in pre-settlement times? *Pteridium* spectra are more or less restricted to diagrams from humid western districts and coastal floodplains, where the spores are at consistently low and discontinuous background levels of 1–2% in the pre-settlement era (Table 1). Yet, following the onset of anthropogenic fire, *Pteridium* dramatically and rapidly increased in the order of 3- to 50-fold in the early to mid-post-settlement period, then declined toward the present (see also McGlone 2001; McGlone et al. 2005).

Discussion

Fire history from radiocarbon-dated charcoal

The mapped pattern of pre-settlement radiocarbon-dated charcoal showed that no eastern South Island district escaped lightning-induced natural fire, despite the pattern being potentially biased to steep slopes. However, when corrected for water-deficit and area, the dated charcoals suggested that drier zones were more prone to natural fire than elsewhere. The impression from Fig. 3 of a greater density of dates in the wetter western mountains probably reflects fires sourced from the lower slopes and floors of drier, inter-fingering valleys and basins juxtaposed with wet upland terrain. Comparison of pre- and post-settlement records of charcoal in relation to water deficit indicated that burning encroached into the naturally fire-buffered humid country with the arrival of humans.

There is no evidence of changes in fire frequency during the early to mid-Holocene. There was small support in the frequency of charcoal dates for an increase in fire frequency after 2600 BP (Leslie & McGlone 1973; McGlone et al. 1995; Ogden et al. 1998), possibly driven by increased seasonality and more frequent droughts associated with intensification of El Niño circulation patterns (McGlone et al. 1992; McGlone & Wilmshurst 1999a). Just three of the 28 pollen diagrams spanning this period show an inverse proportional relationship pre- and post-2600 BP between the pollen of grasses and that of woody species in support of increasing fire frequency (Lake Henrietta, Moar 1973; Kawarau Gorge, McGlone et al. 1995; Duncan Stream, post-5000 BP, McGlone & Moar 1998). Similarly, the associated charcoal spectra from two of those three sites show an increased abundance in the late pre-settlement period compared to the mid-Holocene (Kawarau Gorge, McGlone et al. 1995; Duncan Stream, McGlone & Moar 1998). An increased fire frequency from drying climates would likely be manifest only at more drought-prone low to mid-altitudes in interior districts where these three pollen diagrams and charcoal spectra are sourced.

McGlone and Wilmshurst (1999b) conclude that post-settlement deforestation activity peaked between 700 and 500 BP. Possible economic reasons for land clearance by early Māori (when deforestation peaked and food sources would still have been abundant) include ease of transit and prospecting for the sparse sources of rock suitable for implements. Especially dry summers with föhn winds (El Niño events) superimposed on increased ignition sources may have promoted massive burn-offs of forest, even within vegetation types of lower flammability such as *Nothofagus*. In the Moawhango Ecological District of the central North Island, there is evidence for just two regional conflagrations (550 and 430 BP), which removed much of the primary forest cover across a region measuring 40 km by 30 km that was settled comparatively late in the pre-historic Maori era (Rogers 1987). A similar rapid removal of forest from conflagrations probably occurred in low-relief, eastern South Island regions. Given that Māori settlement is dated at 700–650 BP (McGlone & Wilmshurst 1999b; Wilmshurst & Higham 2004) and that the rapid rise in the frequency of our charcoal radiocarbon dates commenced 1000 BP, the minimum bias of older wood in these dates is about 300–350 years.

Flammability of vegetation

Vegetation flammability has two components: ignitibility and combustibility (Bradstock et al. 2004). Vegetation ignitibility influences the likelihood of fire starting, and has a bearing on fire frequency, whereas combustibility or the capacity of vegetation to sustain fire strongly influences the pattern of fire. Ignitibility would be principally a function of drought and plant life traits. Regarding drought, it is likely that all physiographic classes of forest and scrub experiencing periods of dry tissue would be vulnerable to ignition (including wetlands; Ogden et al. 1998). Plant chemistry also strongly influences ignitibility, with phenolic-rich and schlerophyllous woody plants being particularly prone (Singh et al. 1981; Beard 1990; Bond & van Wilgen 1996). *Prumnopitys taxifolia*, *Podocarpus hallii*, *Phyllocladus alpinus*, *Halocarpus bidwillii*, *Kunzea ericoides*, *Leptospermum scoparium*, and *Dracophyllum* spp., which featured prominently in driest and/or coolest interior forest and scrub (Burrell 1965; Wells 1972; Burrows & Russell 1990; Burrows et al. 1993; Walker et al. 2004; Leathwick et al. unpubl. poster, 2005), tend to be ignition-prone. They were likely ignition-nodes whether as canopy dominants or scattered within otherwise fire-buffered communities. Grasses, especially those with slowly-decomposing litter on cool humid uplands, may also have functioned as ignition sources. Alternatively, low-phenolic trees and shrubs prominent in hardwood communities of warmer environments are unlikely ignition-sources (Bond & van Wilgen 1996: 16; e.g. *Plagianthus*, *Hoheria*, *Sophora*, *Griselinia*, *Myrsine*, *Pittosporum*, *Carpodetus*, *Olearia*, *Carmichaelia*, *Discaria*).

Lightning discharge, as the only pre-settlement ignition event, is comparatively high to the west and low to the east of the Main Divide (Fig. 6). Canterbury and Otago have a discontinuous zone of higher discharge intermediate between the coast and the Main Divide. In Otago, that zone is centred on the interior uplands and basins, with the turbulence possibly generated by westerly airstreams and afternoon convectional thunderstorms in the summer-dry interior (Ogden et al. 1998), but the latter are mostly accompanied by downpours.

In summary, gradients in drought probability, plant chemistry, and lightning discharge all indicate greatest ignition vulnerability and, therefore, fire frequency, in the most climatically and edaphically dry zones of the interior, with their phenolic-rich plants.

The intrinsic features that increase a plant's combustibility include drought, topography, and plant traits, the last influencing fuel load. Steep topography presents natural barriers to fire and produces aspect differences in the moisture content of fuel loads. Alternatively, peneplains, lowland hillcountry, and floodplains would exert little influence on the passage of fire. Combustible fuel loads would be greatest in the phenolic-rich conifer forests and least in the light-canopied and large-leaved hardwood forest of warmer eastern districts.

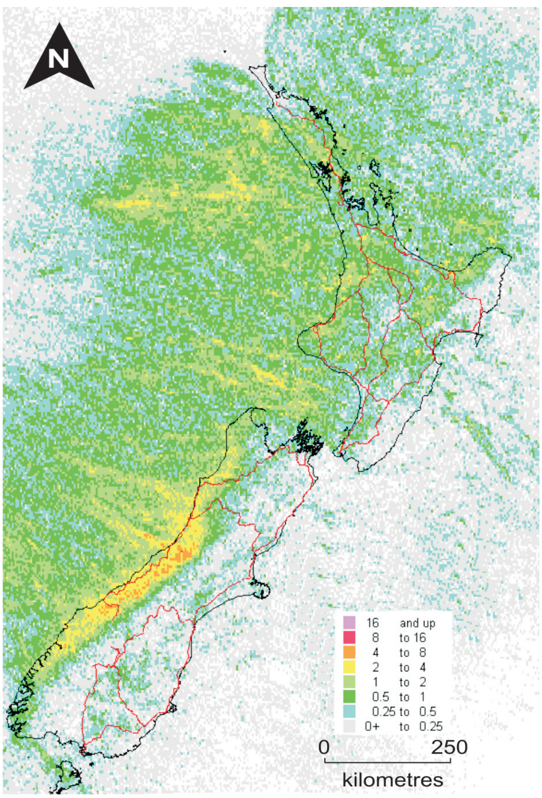

Figure 6. Relative density of lightning strikes per square kilometre from September 2000 to June 2004 for New Zealand and environs (New Zealand Meteorological Service, unpubl. data).

Therefore, our hypothesis is that vegetation flammability (with ignition and combustibility components) was driven principally by key 'ignition and fuel' species with phenolic-rich foliage that were the main ignition nodes for the breakout of fire into less flammable communities.

Evidence of differential flammability of vegetation

Do charcoal and palynological data support our hypothesis that vegetation flammability drove the temporal and spatial pattern of natural fire? Although charcoal durability must vary across species (Burrows 1996), much of our radiocarbon-dated, pre-settlement dataset is derived from phenolic-rich plants of dry interiors such as *Phyllocladus*, the drought-tolerant tall podocarps, *Kunzea*, and *Leptospermum*. Otago's pollen diagrams also provide broad support. On the cool, low-relief and leached eastern peneplains and mountain crests, the evidence is for highly infrequent, patchy fires that solicited slow rates of return of predominantly phenolic-rich, woody vegetation. Where a grass response is evident (Kawarau Gorge, Islands I, Islands II, and Campbell Creek; Table 1), small-grained grass types appear before large-grained types (*Chionochloa*; McGlone et al. 1995, 1997), pointing to their quicker adaptive response to fire (Connor 1964; Connor & Macrae 1969; McGlone 2001). Just one of four diagrams from the eastern peneplains shows evidence of substantial grasses (Clark's Junction; Table 1). Two other Otago diagrams are from lower-altitude, warmer sites with podocarp and hardwood trees and small-leaved shrubs, which have no evidence of local fire in their pre-settlement periods (Idaburn Valley, McGlone & Moar 1998; Earnscleugh Cave, Clark et al. 1996). Overall, only a third of Otago's pollen diagrams show evidence of pre-settlement local fires in their charcoal or Poaceae spectra, all confined to cool humid environments. Wetlands in these districts, with their likely pre-settlement dominant cover of phenolic-rich *Phyllocladus*, *Leptospermum*, *Dracophyllum*, and *Halocarpus* and their summer-dry sedge and rush components, would also have functioned as nodes for the break-out of fire (see also Harris 2002; Johnson 2005).

The hypothesis also receives general support from Canterbury. A cool intermontane-basin site at Duncan Stream, Mackenzie Basin, has a moderate and sustained increase in mainly small-grained grasses and depletion of *Phyllocladus* with the onset of fire after 5000 BP (McGlone

& Moar 1998). There is also evidence for grass expansion at the expense of woody plants at Windy Tarn, Arrowsmith Range (Burrows & Russell 1990). This site corroborates the evidence from several other studies of geomorphic and charcoal data, which shows that patchy *Phyllocladus–Halocarpus* on basin floors and at the treeline acted as fire-nodes within the otherwise *Nothofagus*-dominated mountain catchments of the Waimakariri, Rakaia, and Rangitata rivers' headwaters. Alternatively, Canterbury's warmer lowland hillcountry and floodplains have virtually no evidence of seral grasslands, except one spot sample of high Poaceae from near Christchurch (Moar 1971). If the podocarp–hardwood and hardwood forests and small-leaved angiosperm scrub of this warmer country burned, their conifers were likely fire-nodes, the fires were likely to have been quite infrequent (e.g. 4600-year interval at Broadlands, Christchurch; Table 1), yet probably extensive (on their undulating landforms).

Fire frequency may have been greater than the few and sporadic events recorded by macroscopic charcoal in peat bogs. However, the low frequencies of Poaceae pollen and *Pteridium* spores from the majority of diagrams argue against this. Whereas there is evidence for a grass response to fire only in restricted environments, there is no evidence of fire-selected *Pteridium* fernland in pre-settlement times (see also McGlone et al. 2005).

Conclusions

Radiocarbon-dated charcoals show that most parts of eastern South Island experienced pre-settlement fire. Several lines of charcoal and pollen data and patterns of prehistoric forest and scrub support a model of variable vegetation flammability, with ignitibility and combustibility components, that predicts more fire in cool, seasonally dry or humid interior environments supporting combinations of fire-promoting, phenolic-rich woody vegetation and forbs and grasses. Only within this environmental and biotic envelope was there a feedback relationship between fire and grasses that fostered or perpetuated seral grasses or grassland, particularly in the late pre-settlement period when there was slightly increased fire frequency in drought-prone districts. These zones were relatively small and confined to intermontane basins and subalpine slopes of mountain catchments, whose broken relief or humid climates constrained the spread of fire (cf. 'plains and foothills' of Ogden et al. 1998).

In conclusion, we find no pre-settlement evidence that 'in the drier parts of the South Island rainshadow region there likely would have been mosaics of fire-maintained grasslands and shrublands with more or less extensive forest patches surviving in relatively protected areas' (Bond et al. 2004, p. 124). Instead, feedback between fire disturbance and vegetation flammability perpetuated seral vegetation only in small and predictable parts of rain-shadow South Island mainly in the late Holocene.

Acknowledgements

We thank Matt McGlone and John Barkla for stimulating discussions on the landscape history of eastern South Island, Andrew Lonie for preparing Fig. 1, Amanda Todd for editing a draft, and many helpful suggestions by two anonymous referees for improvement of the manuscript.

References

Archer AC 1979. Plant succession in relation to periodic soil movements in the subalpine zone of the NE Ben Ohau Range, New Zealand. New Zealand Journal of Botany 17: 15–22.

Basher LR, Lynn IH, Whitehouse IE 1995. Geomorphology of the Wairau Plains: Implications for floodplain management planning. Landcare Research Science Series No. 11. Lincoln, Manaaki Whenua Press. 42 p.

Beard JS 1990. Temperate forest of the southern hemisphere. Vegetatio: Acta geobotanica 89: 7–10.

Bond WJ, van Wilgen BW 1996. Fire and plants. Population and Community Biology series 14. London, Chapman and Hall. 266 p.

Bond WJ, Dickinson KJM, Mark AF 2004. What limits the spread of fire-dependent vegetation? Evidence from geographic variation of serotiny in a New Zealand shrub. Global Ecology and Biogeography 13: 115–127.

Bradstock R, King K, Cary G 2004. Flammable connections–a landscape template for understanding the role of fire in shaping Australian vegetation. In: Southern Connections: programme and abstracts of IV Southern Connections Conference, 19–23 January 2004, University of Cape Town, South Africa. P. 65.

Burrell JP 1965. Ecology of *Leptospermum* in Otago. New Zealand Journal of Botany 3: 3–16.

Burrows CJ 1983. Radiocarbon dates from Late Quaternary deposits in the Cass District, Canterbury, New Zealand. New Zealand Journal of Botany 21: 443–454.

Burrows CJ 1996. Radiocarbon dates for Holocene fires and associated events, Canterbury, New Zealand. New Zealand Journal of Botany 34: 111–121.

Burrows CJ, Russell JB 1990. Aranuian vegetation history of the Arrowsmith Range, Canterbury I. Pollen diagrams, plant macrofossils, and buried soils from Prospect Hill. New Zealand Journal of Botany 28: 323–345.

Burrows CJ, Randall P, Moar NT, Butterfield BG 1993. Aranuian vegetation history of the Arrowsmith Range, Canterbury, New Zealand III. Vegetation changes in the Cameron, upper South Ashburton, and Paddle Hill Creek catchments. New Zealand Journal of Botany 31: 147–174.

Clark GR, Petchey P, McGlone MS, Bristow P 1996. Faunal and floral remains from Earnscleugh Cave, Central Otago, New Zealand. Journal of the Royal Society of New Zealand 26: 363–380.

Connor HE 1964. Tussock grassland communities in the Mackenzie Country, South Canterbury, New Zealand. New Zealand Journal of Botany 2: 325–351.

Connor HE, Macrae AH 1969. Montane and subalpine tussock grasslands in Canterbury. In: Knox GA ed. The natural history of Canterbury. Wellington, A.H. & A.W. Reed. Pp. 167–211.

Cox JE, Mead CB 1963. Soil evidence relating to Post-Glacial climate on the Canterbury Plains. Proceedings of the New Zealand Ecological Society 10: 28–38.

Harris W 2002. Variation of inherent seed capsule splitting in populations of *Leptospermum scoparium* (Myrtaceae) in New Zealand. New Zealand Journal of Botany 40: 405–417.

Johnson PN 2005. Fire in wetlands and scrub vegetation: studies in Southland, Otago, and Westland. DOC Research & Development Series 215. Wellington, Department of Conservation.

Johnston WB 1961. Locating the vegetation of early Canterbury: a map and the sources. Transactions of the New Zealand Institute, Botany 1: 5–15.

Leathwick JR, Wilson G, Rutledge D, Wardle P, Morgan F, Johnson K, McLeod M, Kirkpatrick R 2003. Land environments of New Zealand. Auckland, David Bateman.

Leslie DM, McGlone MS 1973. Relict periglacial landforms at Clarks Junction, Otago. New Zealand Journal of Geology and Geophysics 16: 575–585.

Lintott WH, Burrows CJ 1973. A pollen diagram and macrofossils from Kettlehole Bog, Cass, South Island, New Zealand. New Zealand Journal of Botany 11: 269–282.

Mark AF, Dickinson KJM 2003. Temporal responses over 30 years to removal of grazing from a mid-altitude snow tussock grassland reserve, Lammerlaw Ecological Region, New Zealand. New Zealand Journal of Botany 41: 655–668.

McGlone MS 2001. The origin of the indigenous grasslands of southeastern South Island in relation to pre-human woody ecosystems. New Zealand Journal of Ecology 25: 1–15.

McGlone MS, Basher LR 1995. The deforestation of the upper Awatere catchment, Inland Kaikoura Range, Marlborough, South Island, New Zealand. New Zealand Journal of Ecology 19: 53–66.

McGlone MS, Moar NT 1998. Dryland Holocene vegetation history, Central Otago and the Mackenzie Basin, South Island, New Zealand. New Zealand Journal of Botany 36: 91–111.

McGlone MS, Wilmshurst JM 1999a. A Holocene record of climate, vegetation change and peat bog development, east Otago, South Island, New Zealand. Journal of Quaternary Science 14: 239–254.

McGlone MS, Wilmshurst JM 1999b. Dating intitial Mäori environmental impact in New Zealand. Quaternary International 59: 5–16.

McGlone MS, Nelson CS, Todd AJ 1984. Vegetation history and environmental significance of pre-peat and surficial peat deposits at Ohinewai, Lower Waikato lowland. Journal of the Royal Society of New Zealand 14: 233–244.

McGlone MS, Kershaw AP, Markgraf V 1992. El Niño/Southern Oscillation climatic variability in Australasian and South American paleoenvironmental records. In: Diaz HF, Markgraf V eds Historical and paleoclimatic aspects of the northern oscillation. Cambridge, Cambridge University Press. Pp. 435–461.

McGlone MS, Mark AF, Bell D 1995. Late Pleistocene and Holocene vegetation history, Central Otago, South Island, New Zealand. Journal of the Royal Society of New Zealand 25: 1–22.

McGlone MS, Moar NT, Meurk CD 1997. Growth and vegetation history of alpine mires on the Old Man Range, Central Otago, New Zealand. Arctic and Alpine Research 29: 32–44.

McGlone MS, Turney CSM, Wilmshurst JM 2004. Late-glacial and Holocene vegetation and climate history of the Cass Basin, central South Island, New Zealand. Quaternary Research 62: 267–279.

McGlone MS, Wilmshurst JM, Leach HM 2005. An ecological and historical review of bracken (*Pteridium esculentum*) in New Zealand, and its cultural significance. New Zealand Journal of Ecology 29: 165–184.

McIntyre DJ, McKellar IC 1970. A radiocarbon dated Post Glacial pollen profile from Swampy Hill, Dunedin, New Zealand. New Zealand Journal of Geology and Geophysics 13: 346–349.

Moar NT 1970. A new pollen diagram from Pyramid Valley Swamp. Records of the Canterbury Museum 8: 455–461.

Moar NT 1971. Contributions to the Quaternary history of the New Zealand flora 6. Aranuian pollen diagrams from Canterbury, Nelson, and north Westland, South Island. New Zealand Journal of

Botany 9: 80–145.
Moar NT 1973. Contributions to the Quaternary history of the New Zealand flora 7. Two Aranuian pollen diagrams from central South Island. New Zealand Journal of Botany 11: 291–304.
Molloy BPJ ed. 1995. Riccarton Bush: Putaringamotu. Christchurch, The Riccarton Bush Trust. 330 p.
Molloy BPJ, Cox JE 1972. Subfossil forest remains and their bearing on forest history in the Rakaia catchment, Canterbury, New Zealand. New Zealand Journal of Botany 10: 267–276.
Molloy BPJ, Burrows CJ, Cox JE, Johnston JA, Wardle P 1963. Distribution of subfossil forest remains, eastern South Island, New Zealand. New Zealand Journal of Botany 1: 68–77.
Ogden J, Basher L, McGlone MS 1998. Fire, forest regeneration and links with early human habitation: evidence from New Zealand. Annals of Botany 81: 687–696.

Editorial Board member: Richard Duncan

Rogers GM 1987. Vegetation history of Moawhango Ecological Region. Unpublished PhD thesis, Victoria University of Wellington, Wellington, New Zealand.
Singh G, Kershaw AP, Clark R 1981. Quaternary vegetation and fire history in Australia. In: Gill AM, Groves RI, Noble IR eds Fire and Australian biota. Canberra, Australian Academy of Sciences. Pp. 23–54.
Walker S, Lee WG, Rogers GM 2004. Pre-settlement woody vegetation of Central Otago, New Zealand. New Zealand Journal of Botany 42: 613–646.
Wardle P 2001. Holocene forest fires in the upper Clutha district, Otago, New Zealand. New Zealand Journal of Botany 39: 523–542.
Wells JA 1972. Ecology of *Podocarpus hallii* in Central Otago, New Zealand. New Zealand Journal of Botany 10: 399–426.
Wilmshurst JM, Higham TFG 2004. Using rat-gnawed seeds to independently date the arrival of Pacific rats and humans in New Zealand. The Holocene 14: 801–806.