Holocene fire regimes reconstructed from peat core charcoal analysis, in the South Island, New Zealand.

By

Robert A. Rose

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Department of Biological Sciences

University of Canterbury

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Abstract

This study investigates the role that climate and human intervention, have on local and regional fire regimes on the East Coast of the South Island, New Zealand during the second half of the Holocene. Continuous sampling of peat cores, from Travis Swamp, Halls Bush, Glendhu and Pomahaka, at one centimetre intervals allowed the detection of temporal and spatial differences in charcoal abundance. A set of nested sieves, with a mesh sizes of 250 μm, 125 μm and 63 μm, a digital camera, and image analysis software were successfully used to indicate charcoal abundance. Fire regimes prior to human arrival were controlled by fuel moisture levels and restricted by climatic influences on the lack of a suitable ignition source, resulting in significantly higher levels of fire activity in the Otago region compared with Canterbury. Regional fire activities changed over time due to changes in precipitation or evaporative rates. Polynesian exploration of the South island on arrival was rapid, resulting in a sudden increase in the frequency of fire simultaneously throughout the East Coast, approximately 700 years b.p. Deforestation in the Otago region was rapid and complete, due to low moisture levels, compared with a slower more gradual process of forest loss at the Canterbury sites. European settlement resulted in intensive burning associated with to farming practices, throughout the East coast. This change in fire regime resulted in the further deforestation of forest in the Canterbury region. After deforestation had occurred, fire became restricted due to lack of sufficient fuel continuity in the drier areas. Critique of the methodology indicates the most suitable of sieves to utilise in future studies is the one with the 250 μm mesh size. As there is superior accuracy and there is significantly shorter time needed for analysis.

Chapter One

Introduction

The remoteness of New Zealand, with its relatively recent colonisation by humans, provides an excellent setting for a study of palaeoecological change through the Holocene period.

1.1 Fire, an influential phenomenon

Fire is such an important phenomenon due to its ability to transform an environment completely in a very short time frame. Unlike the impact of herbivores, which selectively browse a handful of preferred species, fire devours practically everything in its path and can consume 80% of the above-ground biomass in the burn area (Hochberg *et al.* 1994, Bond and van Wilgen 1996). The shear devastating nature of fire means that even relatively rare recurrences can maintain certain vegetation types in preference of others (Rowe and Scotter 1973, Bond and van Wilgen 1996, Herranz *et al.* 1999, Pitkanen *et al.* 2002).

F. E. Clements' domination of the field of plant ecology from 1905-1945 (Wright and Heinselman 1973) was largely responsible for fire being perceived as a destructive force by the majority of the science community (Dodge 1972, Kilgore 1973), despite earlier publications demonstrating the importance of fire (Maissurow 1935, Garren 1943, Ahlgren and Ahlgren 1960). This line of thinking did not change until the early 1970's when a series of papers reflected a radical change of mind-set within the science community. Fire was no longer perceived as a destructive force but an important force which affected the function and structure of ecosystems (Frissell 1973, Habeck and Mutch 1973, Kilgore 1973, Loope and Gruell 1973, Rowe and Scotter 1973, Swain 1973, Zackrisson 1977, Sugita *et al.* 1994, Zepp and Macko 1994, Zackrisson *et al.* 1996, Wardle *et al.* 1997, Herranz *et al.* 1999, Gollberg *et al.* 2001, Kafka *et al.* 2001, Thonicke *et al.* 2001, Yunli *et al.* 2001, Pitkanen *et al.* 2002, Battle and Golladay 2003, Probst and Donnerwright 2003, Huber *et al.* 2004).

Individual fires do not only remove the majority of the vegetation, but they are capable of changing population dynamics and ecosystem functions such as resource cycling (Gollberg *et al.* 2001), soil nutrient pools (Wright and Heinselman 1973, Reinhardt *et al.* 2001), availability (Kilgore 1973, Debano and Conrad 1978), physical structure of soil (Debano and Conrad 1978, Tilman and Lehman 2001), and vegetation structure and composition (Edwards 1954, Gollberg *et al.* 2001, Probst and Donnerwright 2003), which in turn drastically changes the function of the ecosystem (Kilgore 1973, Clark *et al.* 1989, Dale *et al.* 2001, Morgan *et al.* 2001, Callaham *et al.* 2002, Parshall and Foster 2002, Battle and Golladay 2003).

This influential nature of fire probably makes it the most important disturbance type after human–induced clearance for agriculture and urban development (Williams *et al.* 2004). This is true in almost all environments (Frissell 1973, Pyne and Goldammer 1994, Brown *et al.* 1999, Schwilk and Kerr 2002), be it Arctic tundra, tropical grassland, savannas, boreal and tropical forests, or peat-forming wetlands (Bond and van Wilgen 1996).

1.2 Fire Regime

Fires, rather like insect population outbreaks, have an irregular incidence (Stocks and Kauffman 1994), making the effect of each fire different. The term "fire regime" tries to interpret the net effect of irregular fires over an extended period of time (Li *et al.* 1999, Morgan *et al.* 2001). Description of a fire regime includes many variables, such as return time distribution (frequency) (Turner and Romme 1994, Baker 1995, Li *et al.* 1997), size distribution, intensity, severity (Tande 1979, Glitzenstein *et al.* 1995, Morgan *et al.* 2001) and seasonality, all of which contribute to the local fire regime (Bond and van Wilgen 1996, Umbranhowar 1996, Niklasson 1998, Brown *et al.* 1999, Li 2000, McCarthy *et al.* 2001, Petterson and Reich 2001, Perry and Enright 2002). Variations within these parameters has a huge impact on how a fire behaves (Rebertus *et al.* 1989, Gauthier *et al.* 1996, McCarthy *et al.* 2001), resulting in three discernable fire types Fig1.1; ground fires which smoulder in the organic layers of the soil, surface fires which move just above the soil surface, through to litter and grass and crown fires which move through the canopy at extremely high intensities (Van Wilgen *et al.* 1990, Stocks and Kauffman 1994, Bond and van Wilgen 1996, Pyne *et al.* 1996). The intensity and severity of individual fires progressively increases as fires evolve from ground to surface to canopy (Harmon *et al.* 1986).

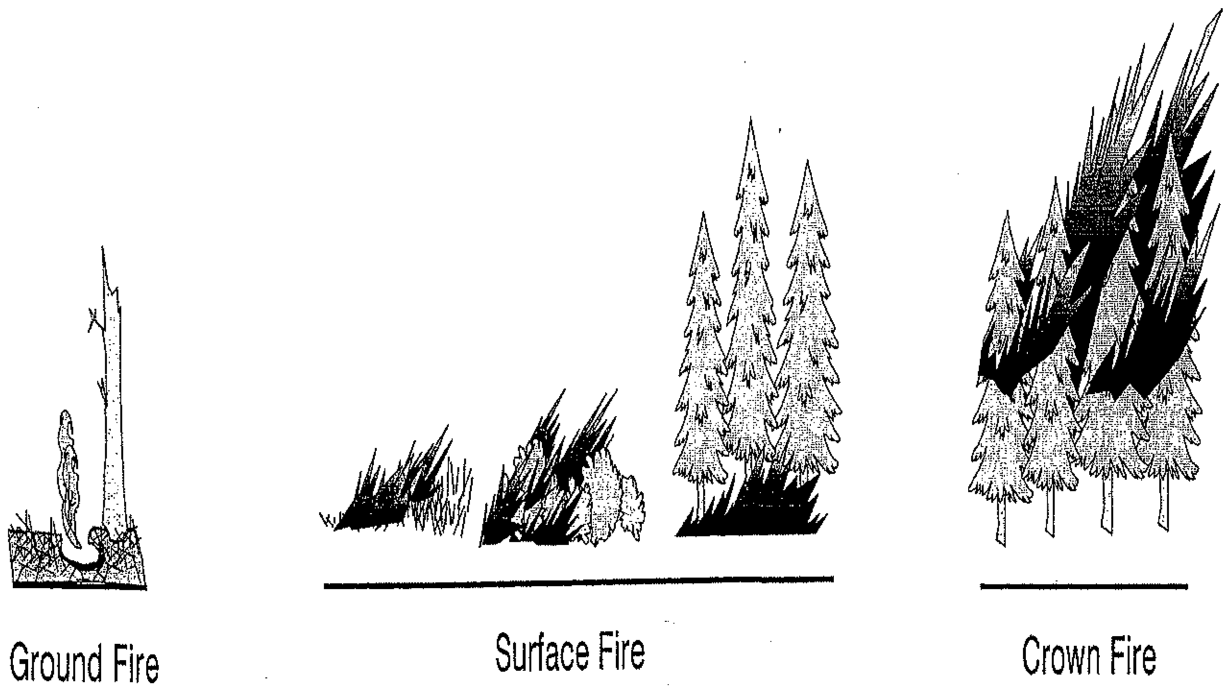


Figure1.1 The three main types of fire from (Pyne *et al.* 1996)

Fire regimes vary considerably between regions due to differences in weather, topography and climate all interacting with each other (in often complex ways) to change the probability of fire over both time and space Table 1.1.

1.2.1 Weather

Weather has an instrumental effect on fire occurrence and behaviour due to its effect on the moisture content of the fuel (ie the above ground and soil surface biomass). Variations in precipitation (Mensing *et al.* 1999, Huber *et al.* 2004), humidity (Shively 1989, Fuller 1991), temperature (Niklasson 1998, Parshall and Foster 2002) and wind velocity (Bessie and Johnson 1995, Moore 2000, Vazquez *et al.* 2002) (Table1.1) are all important, as these variables control the evaporative process and moisture absorption by vegetation and soil (Zackrisson 1977, Johnson 1979, Cwynar 1987, Clark 1989, Johnson and Gutsell 1994, Long *et al.* 1998, Veblen *et al.* 1999, Heyerdahl *et al.* 2001, Kafka *et al.* 2001, Brown and Hebda 2002, Gavin *et al.* 2003, Westerling *et al.* 2003).

Table 1.1 Variation between fire regimes, adapted from (Whelan 1995).

Factor	Effect
Weather	
Rainfall & humidity	Increased fuel moisture, combined with high relative humidity, decreases likelihood of ignition, rate of combustion & rate of spread.
Wind	Causes drying of fuel, increases oxygen availability for combustion, preheats and ignites fuel in advance of the front, can produce ignitions far ahead of the front, wind direction changes can increase fire front.
Topography	Provides variation in local climate (i.e. fuel moisture, relative humidity, interaction with wind), permits pre-heating and ignition for fires burning uphill; can provide natural fire breaks, partially determines distribution of plant communities of different flammabilities.
Climate	Determines type and vegetation productivity and therefor rate of fuel accumulation.
Fuel: Load, Type	determine the maximum energy available to a Fire, arrangement of fuels can affect aeration (tightly packed fuels), vertical spread (i.e. into canopy) and horizontal spread (patchy ground fuel), size distribution of fuel can affect likelihood of initial ignition. Chemistry of fuel can increase flammability (i.e. resins and oils,) or decrease it (ie mineral content).

The effect weather has on the moisture content of available fuel is arguably the most important determinant of fire regimes, as moisture acts as a heat sink, thereby increasing the endothermic input (energy) required to dry out the saturated fuels before ignition can occur.

This increase in latent heat of evaporation, reduces the rate of spread and probability of a fire occurring (Fig. 1.2.); (Rowe and Scotter 1973, Lobert and Warnatz 1993, Bessie and Johnson 1995, Whelan 1995, Pyne *et al.* 1996, Laird and Campbell 2000, Thonicke *et al.* 2001). The importance of fuel moisture on fire spread can be illustrated by eucalypt fuels for which the combustion rate is four times greater at a moisture level of 3% than at 10% (Luke and McArthur 1978). This is why fires in north-western Minnestota tend to occur in unusually dry years (1864, 1878, 1891) (Clark 1989). Thus temperature, precipitation, humidity and wind are vitally important as they interact with each other to influence the moisture content of the available fuel.

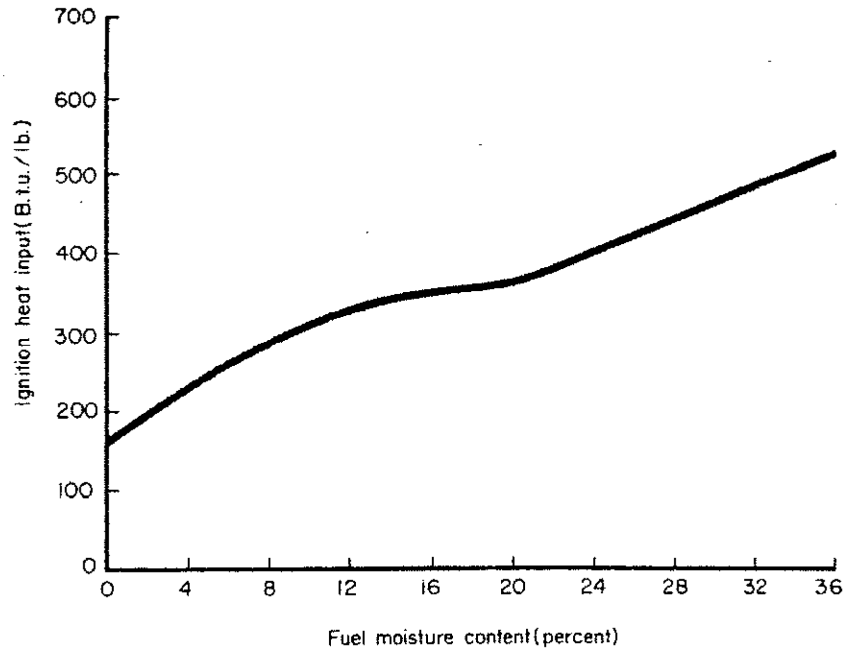


Figure 1.2 Influence of fuel moisture on heat input for ignition (ref)

For this reason climatic phenomena such as the Southern Oscillation (S.O) are important due to their influence on local and regional weather patterns. The influence of the S.O. on fire regimes is very clear over long timeframes e.g. in Alaska 15 out of 17 of the biggest fires occurred during, or just after, El Niño conditions (Hess *et al.* 2001). The Southern Oscillation has become recognised as perhaps the dominant mode of inter-annual oceanographic and climate variability affecting climatic anomalies throughout the world, including New Zealand (Tallis 1975, Swetnam and Betancourt 1990, Salinger 1991, Neal 1993, Basher 1996, McKerchar and Pearson 1996, Mullan 1996, Nicholls 1996, Salinger 1996, Thompson 1996, Zheng 1996, McGlone and Wilmshurst 1999b, Hess *et al.* 2001, Westerling *et al.* 2003). This phenomenon involves the pronounced east-west "seesaw" of tropical convection and atmospheric pressure which creates the phenomena of La Niña and El Niño, which are the extremes of the Southern Oscillation (Mullan 1996, Sutton 1996). The effects of these two phenomena differ dramatically in different parts of the Pacific region (and beyond).

1.2.2 Wind and Topography

Wind also supplies the vital element oxygen to the fire front, increasing the intensity of the reaction. Through manipulating the angle of the flame it makes the flames closer to available unburnt fuel (Fig.1.3.), thereby increasing preheating of fuel and the efficiency of ignition by flame contact (Bessie and Johnson 1995, Moore 2000) thus causing the fire to burn at higher intensity. Consequently, as wind speed increases, the speed of fire rises sharply (Shively 1989). Above a wind speed of 60 km/hr, however, there is little change in fire speed (Baker and Kipfmueller 2001). Thus different regions and habitats will vary drastically due to differences in wind.

The effect of slope (topography) is very similar to that of winds effect on flame angle, with vegetation being brought physically closer to the fire front (Fig. 1.3.). Different aspects also provide variation of local micro-climate and thus ease of ignition.

1.2.3. Climate

While vegetation-type conditions for fire might be ideal, fires will not occur without an adequate ignition source. Several sources of ignition have been observed around the world: extra-terrestrial impact, volcanism etc. (Jones and Lim 2000), but by far the most common cause of natural fire is lightning strikes. Thus climate anomalies such as the Southern Oscillation, which increase the lightning activity, may be vitally important (Hess *et al.* 2001).

Although dry conditions are needed to dry out the fuel, adequate precipitation is required for vegetation productivity and thus fuel build up (White 1979, Pyne and Goldammer 1994, Moore 2000, Pyne 2001, Vazquez *et al.* 2002, Huber and Markgraf 2003). Fires in Africa's savannas, for example, may only burn in years of above–average rainfall when high grass biomass accumulation outstrips the ability of grazers to prevent the build up of fuel (Bond and van Wilgen 1996); Deserts rarely burn for this very reason (White 1979). Thus areas that are prone to fire are then areas that display a variable climate that permit both build-up and drying of biomass/fuel.

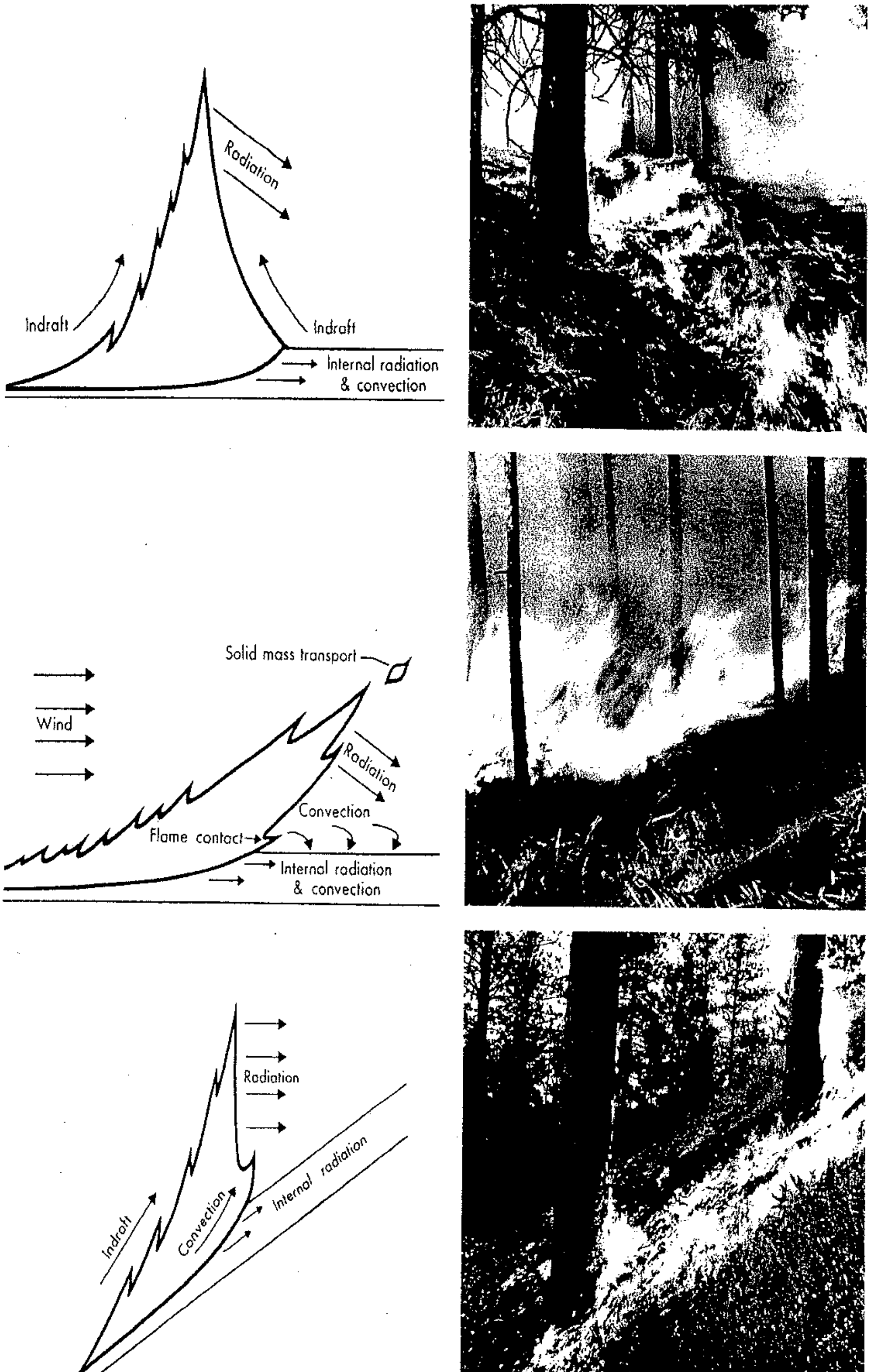


Figure 1.3 Influential nature of wind and Topography (Pyne 1984)

1.2.4. Fuel abundance

Fuel volume increases through yearly increments of accumulating dead material (Maissurow 1935, Olson 1963, Dodge 1972, Heinselman 1973, Rundel and Parsons 1979, Clark 1988b), and thus age of the vegetation (since last disturbance) is important, as it influences the structure and continuity of the fuel matrix, which increase the probability of intense fires, thus the probability of catastrophic fire increases with forest age due to increased continuity (Fig.1.4.)(Rowe and Scotter 1973, Romme 1982, Clark 1988b, Kershaw *et al.* 1994, Stocks and Kauffman 1994, Zepp and Macko 1994, Baker and Kipfmueller 2001, Schwilk 2003). The effects of age are exacerbated by the fact that the probabilities of insect outbreaks, disease epidemics, catastrophic wind storms and flooding also increase with age (Molloy *et al.* 1963, Dodge 1972, Henry and Swan 1974, Harmon *et al.* 1986, De Grandpre *et al.* 2000).

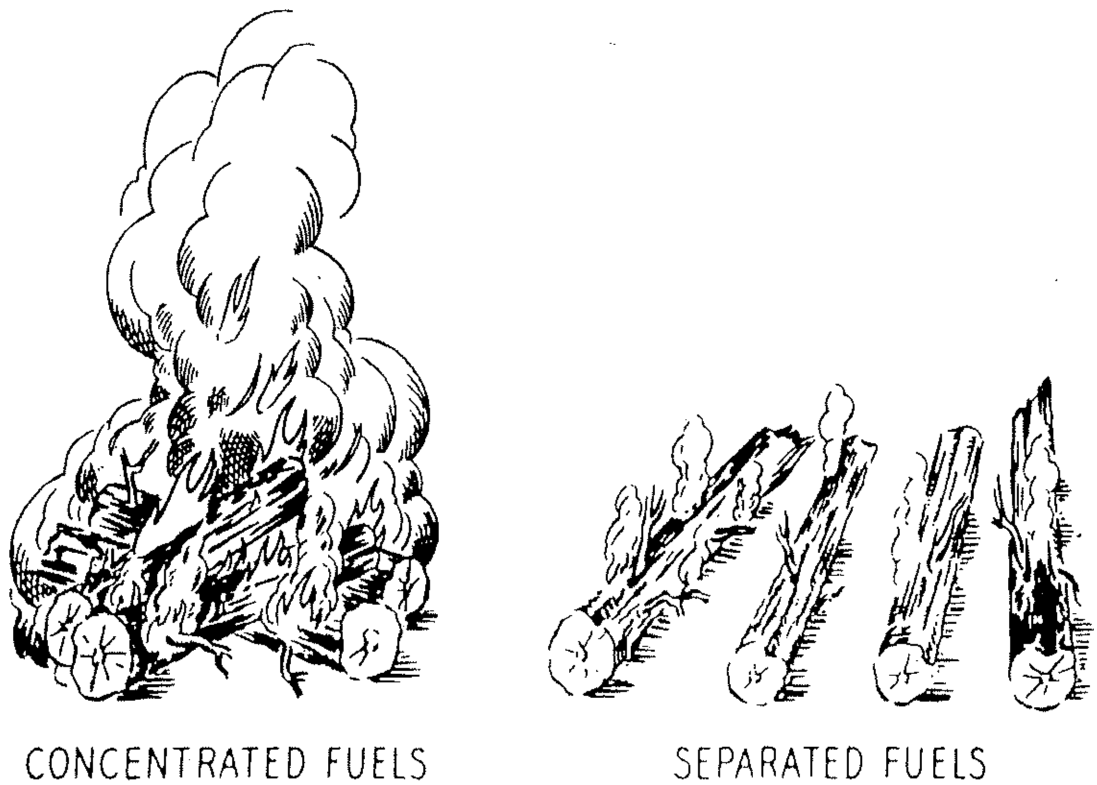


Figure 1.4. The importance of fuel arrangement for sustaining fire: a pile of logs creates a hot fire because the burning logs radiate heat to each other. When the pile is broken up, radiant heat transfer is reduced (Pyne *et al.* 1996)

Not only does climate control the rate of productivity but the type of fuel present in the area. This is important as it influences the chemical composition and structure of fuel which partially determine the intrinsic flammability of the vegetation (Fig.1.5.)

1.2.5. The chemical composition of fuel

Volatile resins and oils in the fuel have a huge impact on flammability (Fig 1.5) (Kilgore 1973, Rowe and Scotter 1973, Rundel and Parsons 1979, Van Wilgen *et al.* 1990, Stocks and Kauffman 1994, Bond and van Wilgen 1996, Perry and Enright 2002). Resins and oils are driven out of the fuel at relatively low temperatures, instantaneously exploding into flames as they volatilize. The hot gasses, together with radiation from the flames, rapidly warm adjacent un-burnt fuels, accelerating the rate of pyrolysis due to extra input of energy and so intensifying the burning process. The high flammability of some Australian forests is partially due to the high levels of resins and oils found in many of the dominant species, such as eucalyptus. Eucalypt leaves, oven-dried at 110°C, burnt with lower heat energy yield than un-dried leaves, due to loss of volatile oils during the drying process (Perry and Enright 2002).

High mineral content, on the other hand, interferes with pyrolysis, by creating large amounts of ash and promoting char formation. This in turn begins to suffocate the fire of oxygen. Many forest and grasslands species with high inorganic mineral contents have low flammability levels and burn relatively slowly, and may therefore act to 'dampen' the fire, instead of fueling it (Vines 1981). The balance of resin/oils and mineral content explains some of the differences in susceptibility of plant communities to fire (Fig. 1.5).

1.2.6. Fuel size (Surface area to volume ratio)

This relationship between fire and oxygen means densely packed fuels act as if they have a low surface area to volume ratio and often burn at a reduced intensity or not at all. The size of particles and their spatial arrangement influence the rate of spread of a fire because they determine how much of the fuel is in contact with atmospheric oxygen (for combustion) at any one time (Fosberg and Levis 1994). If the air cannot freely circulate around it, a fuel will burn with reduced vigour (Fuller 1991). Thus fuels with large surface to volume ratios like grass, reach pyrolysis temperatures quickly (Fosberg and Levis 1994), while fuels with small surface to volume ratios like logs, burn slowly.

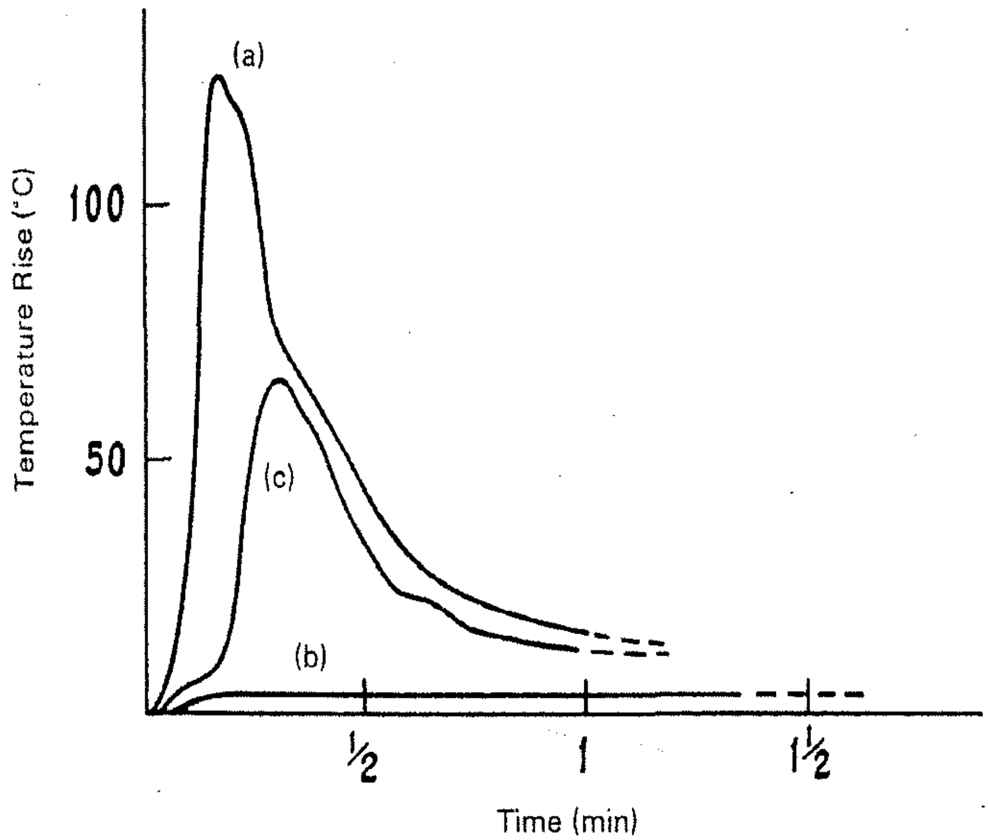


Figure 1.5. Temperature traces obtained by burning leaf samples in a flow calorimeter: (a) 20 g sample of oven-dried Eucalyptus leaves with high oil content burned rapidly; (b) 20 g sample of oven-dried leaves of *Phytolacca octandra* with high mineral content smouldered only; (c) 20 g sample of leaves of *P.octandra* containing 3 per cent absorbed essential oils - flaming was pronounced, although the leaves were only partially consumed (Vines 1981).

Ultimately all of the factors mentioned in (Table 1) shape the fire regime of a given area and it is therefore crucial to take into account these variables when comparing contrasting environments (Rundel and Parsons 1979, Van Wilgen *et al.* 1990, Johnson and Larsen 1991, Fosberg and Levis 1994, Stocks and Kauffman 1994, Bessie and Johnson 1995, Clark and Royall 1996, Cheney and Sullivan 1997, Higgins *et al.* 2000, Millspaugh *et al.* 2000, Carcaillet *et al.* 2001a, Carcaillet *et al.* 2001b, Vazquez *et al.* 2002, Camill *et al.* 2003). Thus different vegetation types have significantly different flammability due to differences in these factors (Fig. 1.6.).

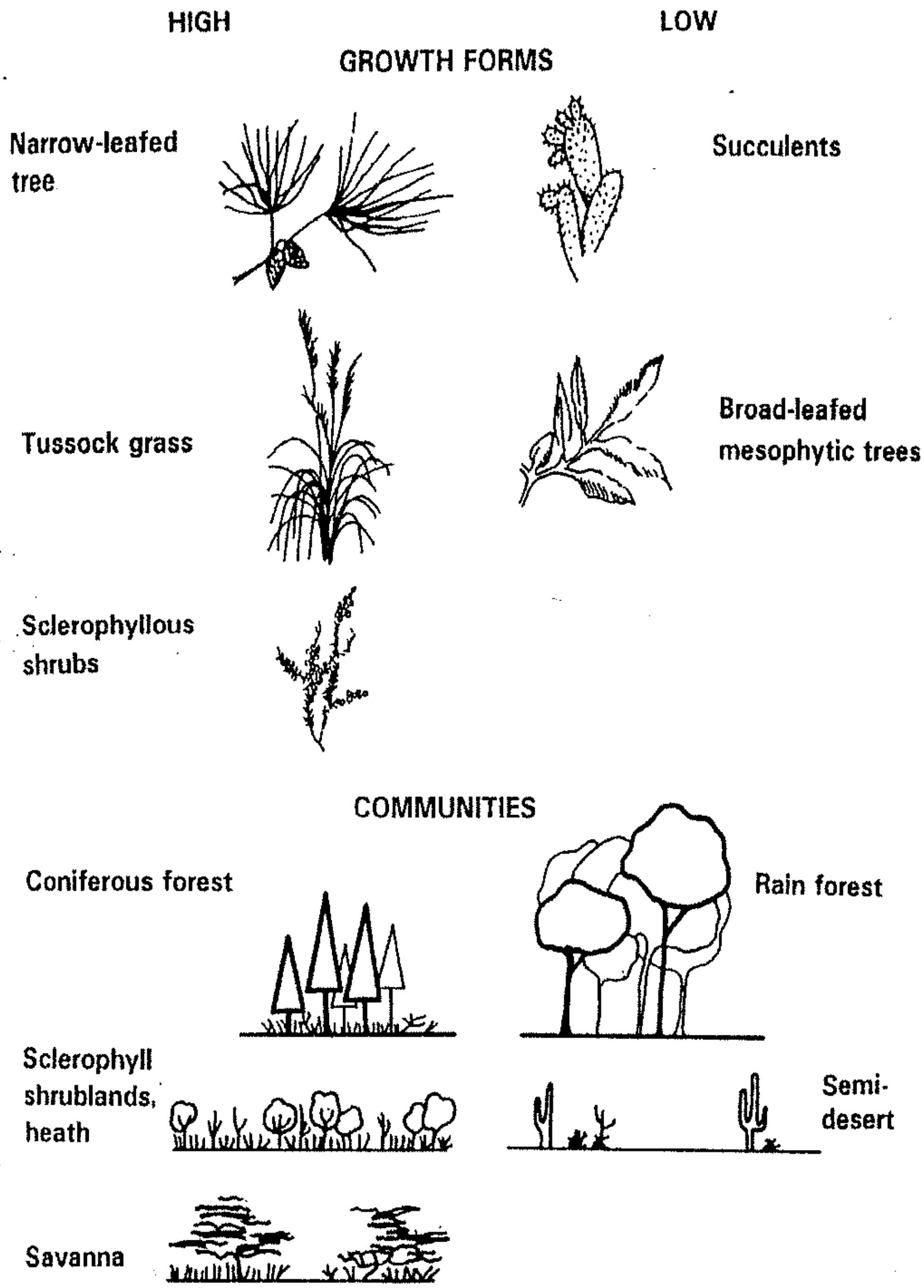


Figure 1.6. Vegetation structure greatly affects the flammability of an ecosystem (Bond and van Wilgen 1996)

1.3 Effective fire management

Effective management of any ecosystem for maximum biodiversity requires an understanding of the role and impact of fire on the ecosystem (recent past and present) and whether management actions may change that role. Such an analysis often assumes a distinction between natural fires (e.g. lightning ignitions) and anthropogenic fires. This distinction is often complicated by the fact that humans have been influencing fire regimes for over 1.5 million years (Brian and Sillen 1988, Pyne 1989, Hansen 2001, Scott 2002), either as a deliberate management tool or through accidental ignition. Currently humans influence the fire regime by affecting both the initiation and the suppression of fires and these behaviours change through time due to different cultures and knowledge of fire importance. The importance of fire was not fully appreciated until relatively resently, this is reflected by the extensieve reference list, which is biased towards the last ten years eg (Frissell 1973, Swain 1973, Tallis 1975, Haines *et al.* 1983, Frelich and Lorimer 1991, Baker 1992, Bradshaw *et al.* 1994, Clark and Patterson 1994, Fosberg and Levis 1994, Glitzenstein *et al.* 1995, Mwaria-Maitima 1997, Bergeron *et al.* 1998, Kitzberger and Veblen 1999, Veblen *et al.* 1999, Harrod *et al.* 2000, Li 2000, Niklasson and Granstrom 2000, Gollberg *et al.* 2001, Moody and Martin 2001, Tilman and Lehman 2001, Caldararo 2002, Bowles *et al.* 2003, Guyette *et al.* 2003, Huber and Markgraf 2003).

In most regions humans are the leading causes of fire (Cofer *et al.* 1994, Baker 1995, Vazquez and Moreno 1998, Mensing *et al.* 1999, Tinner *et al.* 1999, Li 2000, Tinner *et al.* 2000, Cardille and Ventura 2001, McCarthy *et al.* 2001, McGlone 2001, Tilman and Lehman 2001, Parshall and Foster 2002, Vazquez *et al.* 2002, Laterra *et al.* 2003). In a California (US) regional survey more than 90% of all forest fires were reported as human-caused (Caldararo 2002). Similar figures have been found in Siberia and Mexico (90% and 95 % respectively; (Caldararo 2002). This human influence on fire regimes results in a distinct increase in fire frequency after colonisation of areas previously free of humans (Fig. 1.7.) (Heinselman 1973, Edney *et al.* 1990, Motzkin *et al.* 1993, Bradshaw *et al.* 1994, Kershaw *et al.* 1994, Hoffmann 1996, Umbranhowar 1996, McGlone and Moar 1998, Moore 2000, Tinner *et al.* 2000, Turney *et al.* 2001, Pitkanen *et al.* 2002, Szeicz *et al.* 2003). Thus the history of fire is inextricably intertwined with the history of humans (Pyne 1989). Anthropologists have recorded habitat burning by nearly all known populations, including Polynesian and European (McGlone 1983, McGlone and Bathgate 1983, Davidson 1984, Caughley 1988, McGlone 1989, Anderson and McGovern-Wilson 1990, Kirch 1996, Hall and McGlone 2001, McGlone 2001, Caldararo 2002).

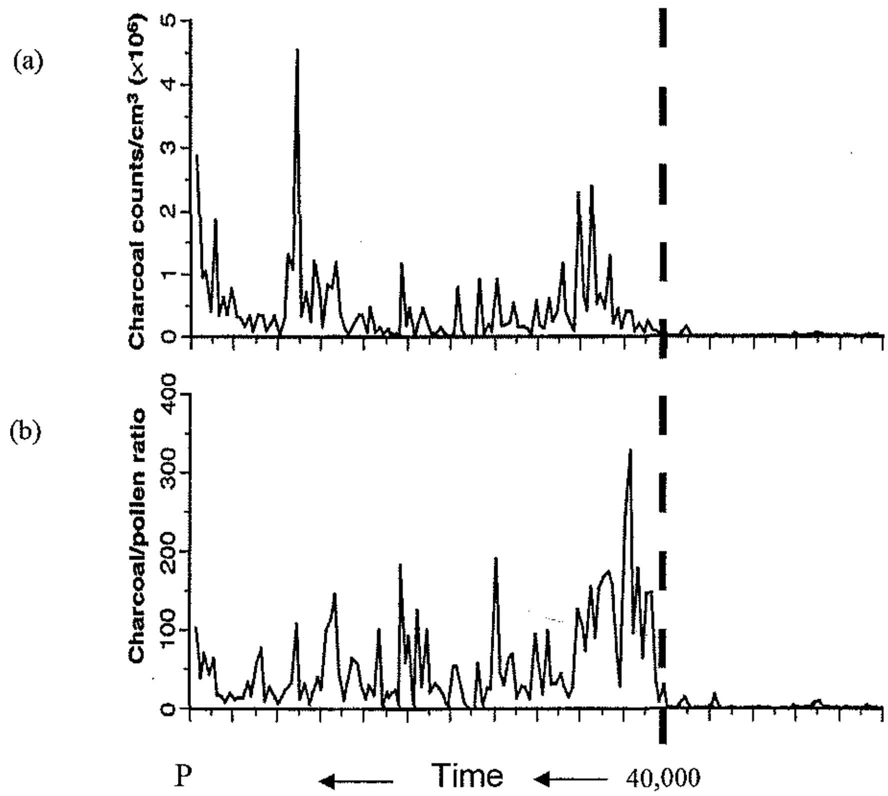


Figure 1.7 Human impact on fire regime in Australia. Both charcoal (a) and pollen records (b) changed suddenly due to Aboriginal arrival in Australia nearly 40,000 years ago (Turney *et al.* 2001).

85-90 % of the pre-Polynesian landscape of New Zealand was clothed in temperate rain forest (Fig.1.8.), with grassland and scrubland being mainly restricted to above the tree line (McGlone 1989). Since then 75 per cent has been cleared (Ogden and Stewart 1996). The arrival of Māori on New Zealand's east coast was the catalyst for drastic changes in local and regional fire regimes and consequent deforestation (Burrows 1960, Molloy *et al.* 1963, Cameron 1964, Molloy 1977, McGlone 1978, Burrows 1983, McGlone 1983, Bussel 1988, McGlone 1989, McGlone *et al.* 1994, McGlone and Basher 1995, Elliot *et al.* 1997, Wilmshurst *et al.* 1997, Newnham *et al.* 1998a, Ogden *et al.* 1998, McGlone and Wilmshurst 1999b, 1999a, Holdaway and Jacomb 2000, Hall and McGlone 2001, McGlone 2001, Stevenson *et al.* 2001).

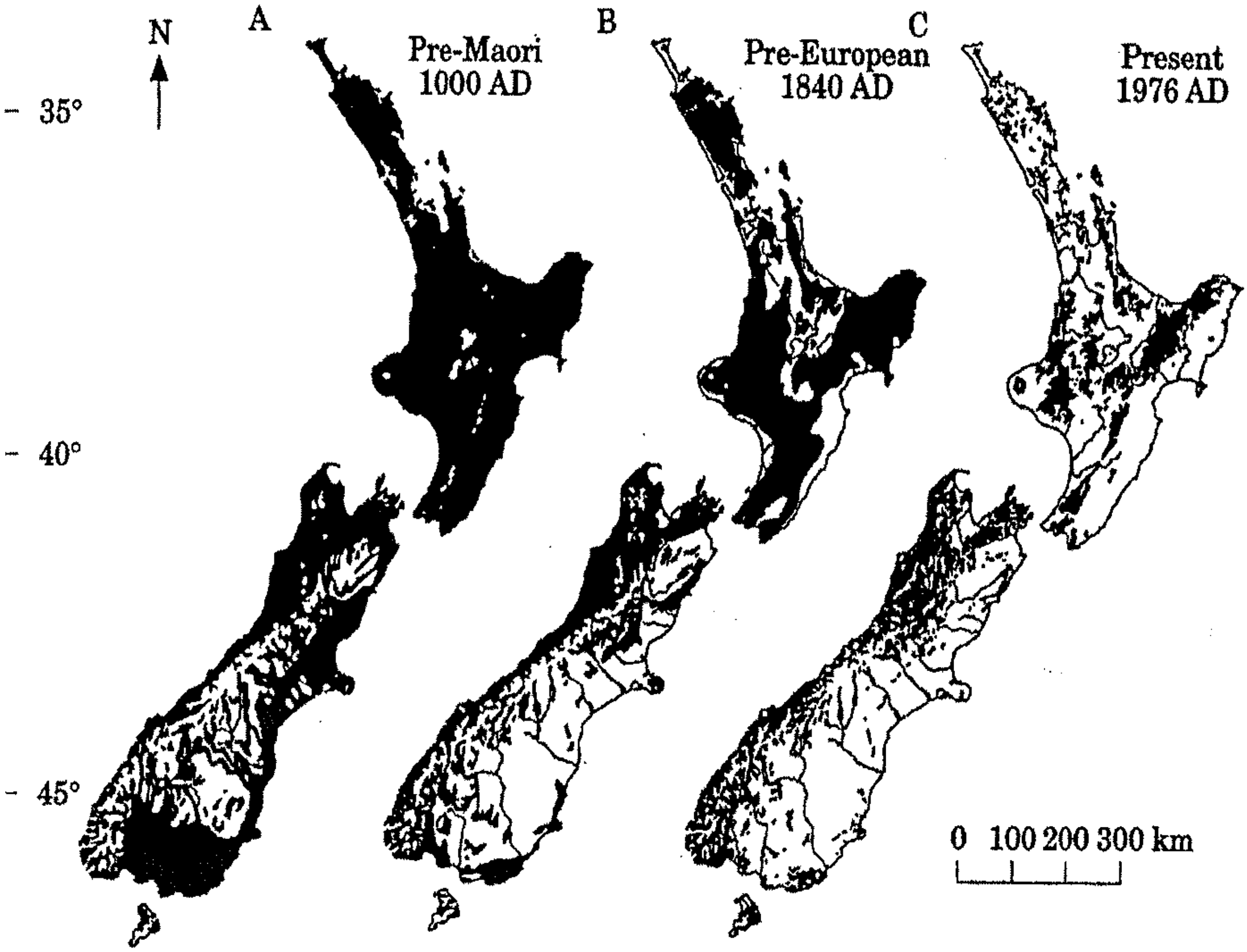


Figure 1.8. A-C, Progressive loss of forest (black shading) in New Zealand from 1000 AD to present, adapted from Wendelken (1976). Remaining vegetation restricted to areas with relatively high precipitation, based on Tomlinson 1976 (Ogden *et al.* 1998).

This pattern of burning and replacement of vegetation with fire-tolerant species is unlikely to be climate-driven, as such an overwhelming climate-driven change is unlikely to occur over such a short time frame (Turney *et al.* 2001).

1.3.1 Human induced change

Fires in ecosystems clearly do not occur in isolation; they are influenced by, and in turn influence, the environment (Tande 1979, Garstang *et al.* 1994, Laterra *et al.* 2003). Thus a fire episode of sufficient size can create a positive feedback loop in which there is an increase in flammability, increasing the size and frequency of fires over time, drastically affecting the composition and structure of the vegetation, converting an ecosystem with low flammability to one with high susceptibility (Brown *et al.* 1999, Enache and Prairie 2000, Stevenson *et al.* 2001, Perry and Enright 2002, Langevelde *et al.* 2003). Pollen and charcoal data from lake sediments in eastern Finland indicate considerable changes in forest structure and an increase in fires (Pitkanen *et al.* 2001). These changes in vegetation type and structure mean that the fires that occur today will be significantly different from naturally occurring fires that began influencing the landscape approximately 325 million years ago (Scott *et al.* 2000).

Because of the influential nature of fires, ecosystems have undoubtedly adapted through natural selection, at least to some degree, to coincide with the change of fire regime induced by human intervention. This is particularly the case in fire-prone ecosystems in Africa (Bond and van Wilgen 1996), Australia (Yates *et al.* 2003) and California (Mensing *et al.* 1999), with plant life histories being fine-tuned to particular regimes (Amiro *et al.* 2001, Keeley and Bond 2001).

Mutch (1970) argued that fire-dependent fire communities burn more readily than non-fire-dependent species as natural selection has favoured development of characteristics that make them more flammable (Fig 1.5.) Retention of dead branches, fine branching patterns that influence the air/fuel mix, and the presence of volatile oils have all been cited as potential flammability-enhancing traits. These characteristics were selected because the growth and reproductive disadvantages these plants incur from being burnt at frequent intervals are outweighed by the advantages of displacement or exclusion of competitive species which are slower to recover after such disturbance (Heinselman 1973, Kilgore 1973, Veblen and Markgraf 1988, Pyne 1989, Edney *et al.* 1990, Clark and Patterson 1994, Fosberg and Levis 1994, Pyne and Goldammer 1994, Bond and Midgley 1995, Bond and van Wilgen 1996, Ogden *et al.* 1998, Brown *et al.* 1999, Grau and Veblen 2000, Carcaillet *et al.* 2001a, Heyerdahl *et al.* 2001, 2002, Schwilk and Kerr 2002, Huber and Markgraf 2003, Schwilk 2003).

1.3.2 Fire constrained by fuel

A fire in any environment, be it natural or human-caused, is fundamentally affected by the fuel matrix that it occurs in (Clark 1989, Huber *et al.* 2004). Since both natural and anthropogenic fires are intrinsically linked with available fuel (Heinselman 1973, White 1979, Romme and Knight 1981, Carcaillet 1998, Hely *et al.* 2000, Higgins *et al.* 2000). Occurrence of either will preclude the other until vegetation biomass is high enough to carry another fire. After a fire has occurred, there is generally insignificant fuel to support more than light surface fires for a period of time which is ecosystem-dependent (Clark 1988b). Thus the time since the last fire is often significant (Habeck and Mutch 1973) in fire-prone ecosystems (Luke and McArthur 1978, Clark 1988a, 1988b, Whelan 1995, Carcaillet *et al.* 2001a). Thus anthropogenic fires could prevent natural fires from occurring simply by limiting fuel availability, hence the Aboriginal use of patch burning to control wildfire from lightning strikes. This importance of fuel was clearly stated by William E Towell who stated in a talk " … A fire control agency's worst enemy may be its own efficiency, the longer fuels go without burning, the greater the fuel accumulation and the greater the hazard…" (Dodge 1972).

1.3.3 Climatic change

As previously mentioned in earlier sections (Table 1.1), climate and weather are instrumental in determining the nature of fire regimes. Thus for effective management one has to be aware of how the climate of the area has changed over time and the implications this has on the fire regime. Changes in climate make comparisons between two different time periods difficult as conditions are far from constant, especially when humans have been brought into the picture in the interim (Scott 2002).

In anthropogenic landscapes, the relationship between fire characteristics and climate may be less pronounced (Veblen *et al.* 1999, Vazquez *et al.* 2002). Since there is a higher probability of ignition due to more frequent and increased initial energy input, thus even in damp conditions a fire may eventuate. Compounding this, humans have the ability to modify the fuel bed by grazing, thinning, planting etc. However, moisture content of fuel still limits fire occurrence in extremely wet environments, resulting in these areas remaining largely undisturbed by fire.

1.4 New Zealand colonisation

On the timescale of human populations around the world, New Zealand was colonised relatively recently (Table 1.2), few landmasses having a shorter human prehistory (McFadgen 1982, Anderson 1991a, Ogden *et al.* 1998, Hogg *et al.* 2003). While it was the last large landmass to be colonised (McGlone *et al.* 1994), there is considerable debate over the timing *al.* 1998a, Newnham *et al.* 1998b, Hogg *et al.* 2003). Scientist have been unable to settle on one agreed time of human arrival. Estimated dates still range from 500 to 2000 yr b.p. (Fig 1.9). Some believe that New Zealand was colonised up to 2000 yr b.p. (Sutton 1987), suggesting that it took a long time for the settlers to adapt to the new environment. Other scenarios suggest different periods of settlement, and thus rates of adaptation, 'short' (600 - 800 yr b.p.), or 'intermediate' (c. 1000 yr b.p.) (Davidson 1984). This uncertainty in the length of settlement makes a great difference to the way we interpret ecological change induced by human activity (McGlone and Wilmshurst 1999a). Despite this uncertainty, the majority of the dates fall between 800 and 1000 years b.p.

Table 1.2. Time of newly colonised countries

Country	Time b.p.
USA	12000 yrs
New Caledonia	3,500 yrs
New Zealand	500-2000 yrs

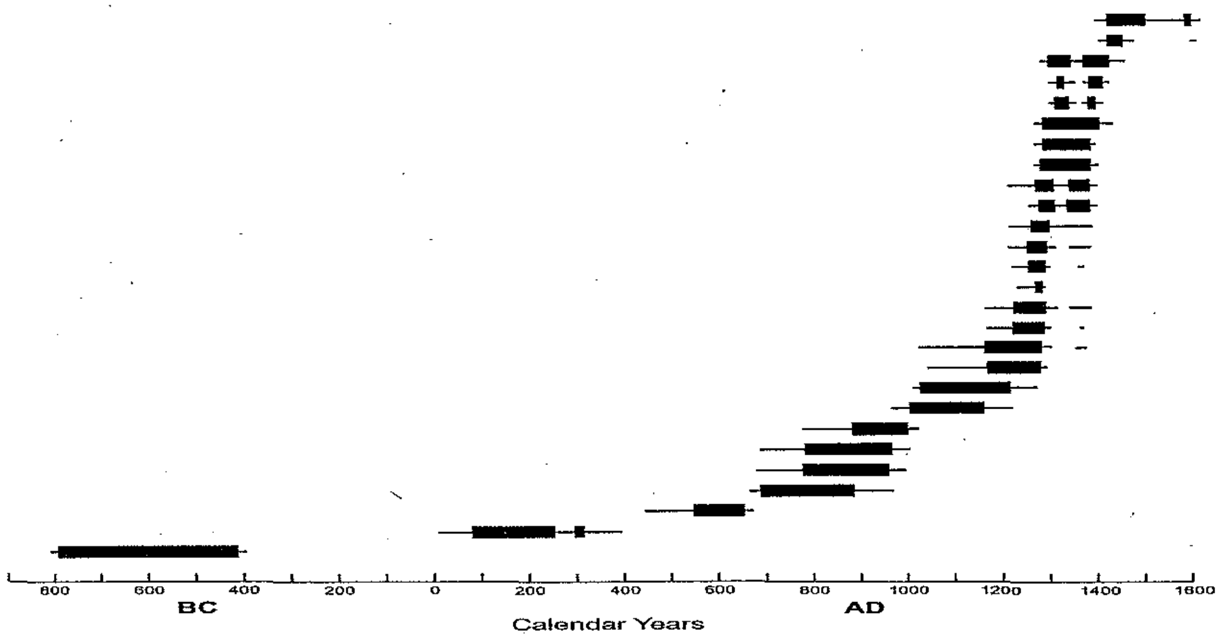


Figure 1.9 Time of arrival controversial; proposed date of arrival spread out over a relatively long time period. Individual box plots indicate the proposed period of settlement by different scientists (McGlone and Wilmshurst 1999a).

Recent radiocarbon dating of bone gelatin from Pacific rats (*Rattus exulans*) found in New Zealand, yield dates of approximately 2000 yr b.p. (Holdaway 1996). These dates support Sutton's (1987) "long prehistory hypothesis". For successful colonisation to have occurred, 2000 yr b.p. implies that there was an archaeologically invisible period of about 700 – 1000 yrs (McGlone and Wilmshurst 1999a), as it is not until 750-1000 yr b.p. that both archaeological and environmental data show evidence of humans and major environmental change. This length of invisible period is extremely unlikely, as even small populations leave highly visible signs of their presence, especially because Polynesian culture habitually exploits the sort of coastal resources that leave durable archaeological remains (Anderson 1991a, McGlone *et al.* 1994). An invisible period would require that population throughout New Zealand would have to be less than one thousand and very dispersed (McGlone *et al.* 1994). It also seems incongruous that the first settlers ignored obvious big game animals, including moas (Dinornithiformes) and seals, for centuries before attacking them enthusiastically (Anderson 1991a). Thus, even if these earliest dates are correct, this first colonisation could not have been successful. Further doubts are raised by dates from egg shell and charcoal in the same area in which the rat bone was collected, which differed significantly from the rat bone dates. This questions the reliability of rat bone collagen in routine age measurements (Anderson 1996).

Anderson argues that the effects of colonisation were immediate and occurred 600-800 years ago. These dates coincide with a dramatic change in the environment that is clearly visible in palaeoecological records (Anderson 1991b, McGlone *et al.* 1994, Newnham *et al.* 1998b). A large degree of diversity, especially within wood carvings and adze assemblages, contradicts the assumption of a single and late first colonisation (Sutton 1987). The massive increase in microscopic charcoal found in lake and bog sediments 1000 yrs b.p. is a clear indication of increased fire intensity. Such an increase is unparalleled in the previous 8000 yrs (McGlone and Wilmshurst 1999a). At the same time, there is a sharp decrease in tree pollen. Instead, pollen and spores of seral scrub, bracken or grassland species dominate (McGlone 1983). There is also a large increase in archaeological evidence that coincides with this transition of vegetation composition (McGlone *et al.* 1994). I think colonisation of New Zealand was swift and environmental impacts were felt virtually immediately after landing approximately 700 years ago.

New Zealand's late discovery, due to its isolation in the Pacific Ocean, and its richness in terrestrial geological information makes it an ideal natural laboratory to understand how humans have changed fire regimes and consequent impacts (Wilmshurst *et al.* 1997, Carter and Lian 2000).

1.4.1 New Zealand vegetation

The vegetation cover of New Zealand has undergone several changes since the end of the last glaciation period 14,000 yr b.p. (McIntyre and McKellar 1970, McGlone and Bathgate 1983, Elliot *et al.* 1997, McGlone and Moar 1998, Hall and McGlone 2001). Changes in climate resulting in vegetation changes have a major effect on local and regional fire regimes, as vegetation type influences the susceptibility to fire through adjusting microclimate, chemical make up, type and amount of fuel, as discussed in the previously section (Ogden *et al.* 1998).

1 Grassland period (final stages of glaciation, severe climate >10,000yr B.P.).
2 Podocarp period (uniformly wet and probably warm climate > 4,000 yr B.P.)
3 *Nothofagus* forest (grassland mosaic period, deterioration of climate >1000yr B.P.)
4 Grassland period (human intervention causing increased fire frequency ? < present)
refer to table 1.3

Table 1.3 Changes in vegetation since the last glaciation (McGlone and Bathgate 1983)

Yrs b.p	**vegetation and pollen zone**	**climate**
100	European pastures and plantations	no change noted
1000	deforestation of lowlands by Polynesian settlers	no change noted
4000	partial replacement of Podocarpus-Dacrycarpus forest by *Dacrydium cupressinum* and *Nothofagus menziesii*	cool, moist climate close to that of the present
7000	Podocarpus-Dacrycarpus dominant but slow spread of *Dacrydium cupressinum* and *Nothofagus menziesii*	increased rain fall, storminess and decreasing temperature
9400	*Podocarpus spicatus* – Dacrycarpus forest dominant	warmer, milder and slightly drier, climate
12000	*Coprosma- Myrsine* dominant shrubland-grassland on uplands; spread of low forest of *Hoheria*	Slowly increasing temperature and rainfall
14000	Grasslands and shrublands dominant, sparsely vegetated lowlands	cool annual temperature up to 5 °C lower than present

The predominant view amongst New Zealand plant ecologists has been that the forests were rarely burned prior to the arrival of people, a correlation based on the lack of fire adaptations in the flora (Burrows 1990, McGlone *et al.* 1997). However different vegetation types do have different susceptibilities to fire. *Nothofagus* forests have a relatively low wood volume, a high mineral content in the leaves and wood, and their litter decomposes relatively quickly, thereby reducing the likelyhood of ignition. Despite this, extensive areas of *Nothafagus* forest in drier areas have been transformed into tussock grassland by fire. Podocarp-hardwood forests, on the other hand, have a higher amount of structure and species diversity, and thus probably a higher intrinsic flammability if they were subjected to extreme drought. However these forest types (now) characterize the wetter montane zones, where fire appears to be infrequent due to the high levels of precipitation. Shrublands and heaths include the most fire prone of New Zealand's community types and contain species with some fire adaptations (*Leptospermum scoparium*) (Ogden *et al.* 1998), however Manuka's adaptation is serotiny and may reflect that it was a relatively recent immigrant from Australia. Tussock grasslands carry a large amount of dead biomass as leaf bases and sheaths, which predispose these communities to fire. This characteristic of tussocks has been exploited by sheep grazers who burn tussock to stimulate positive productivity (McLeod and McLeod 1977).

1.4.2 What causes climate variations in New Zealand

The topography of New Zealand is highly diverse and has an instrumental effect on local and regional precipitation (Mullan 1996, Thompson 1996). The Southern Alps create a rain shadow across the east coast of the South Island (Fig.1.10) (McGlone and Moar 1998), dividing the country into two dramatically different climate regions, with the West Coast being by far the wettest area, whereas the area to the east of the mountains, just over 100 km away, is the driest part of the South Island (Garnier 1958, Neal 1993). The effects of the topography vary over time, depending on the dominant wind direction.

Even within New Zealand there is variation in the effect of the Southern Oscillation. An El Niño results in strong westerly and southerly winds, especially in spring and summer. The weather over most of the country becomes cold and windy. Our climate records show that the weather is very cloudy and wet on the South Island West Coast, Southland and Otago, while in the rest of the country conditions are dry and windy and often suffer prolonged drought (Salinger 1996). La Niña on the other hand causes north-easterly winds, resulting in hot dry weather and often throwing the lower South Island into severe drought (Salinger 1996). McKerchar and Pearson (1996) found that low inflows of water in to the lake in summer were significantly more likely when the spring Southern Oscillation was positive (La Niña conditions).

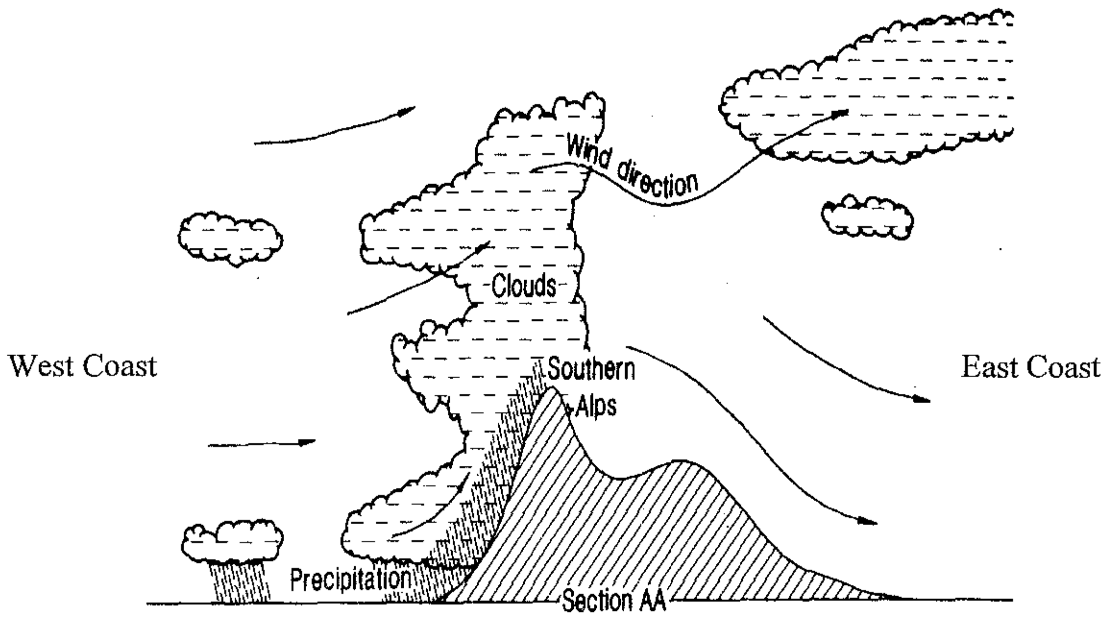


Figure 1.10. The Southern Alps' effect on precipitation.

Lightning is the only plausible natural ignition source in the South Island. Since lightning in New Zealand is often accompanied by torrential rain, the number of natural ignitions is extremely low. Lightning activity also varies dramatically between regions, with Otago getting significantly more lightning strikes than the rest of the South Island (McGlone 1989, Rogers and McGlone 1989, Burrows 1996).

1.5 How do we reconstruct past fire events and regimes

The study of fire history has become increasingly popular in the last few decades and three main sources of information are used: dendrochronological, pollen and charcoal data (Gedye *et al.* 2000). Each type of data has strengths and weaknesses for describing fire frequency, variability, season, severity , extent and location (Morgan *et al.* 2001).

1.5.1 Dendrochronology

Dendrochronological analysis is a direct method of reconstructing fire history. It involves close examination of tree-ring scarring on fire-resistant trees (Fig.1.11.) and is one of the most common ways of studying past fires (Whitlock 2001). Low-severity ground fires typically scorch, but do not kill, fire-resistant species, leaving pronounced scarring at the base of the cambial layer. This scarring results in damaged or truncated tree rings, making it possible to pinpoint the timing of individual fires through careful analysis. The annual, or even seasonal, nature of growth rings means that the timing of past fires can be spatially specific with a high precision (Fritts and Swetnam 1989, Agee 1993, Pyne and Goldammer 1994, Whitlock *et al.* 1994, Whitlock and Millspaugh 1996, Morgan *et al.* 2001, Whitlock 2001). This precision in regions where seasonal climate induces rhythmic growth patterns is unsurpassed (Niklasson 1998).

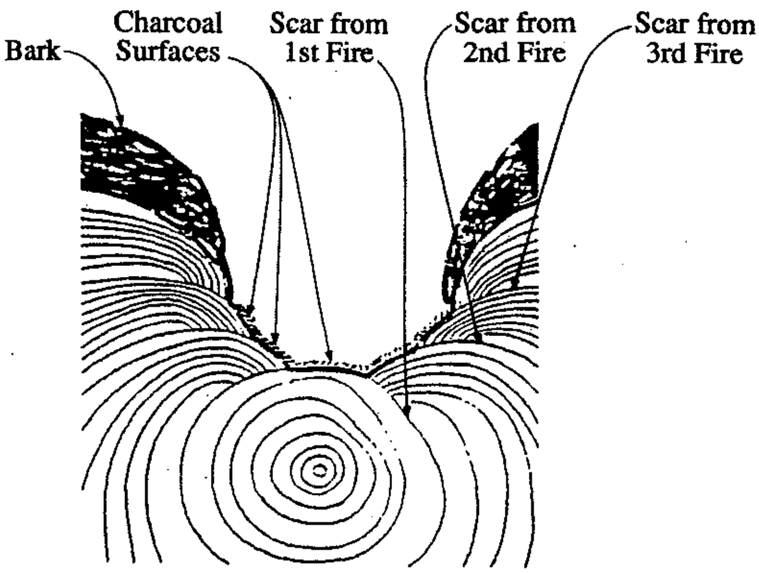


Figure 1.11 Scars due to fire, prominent in seasonal growth rings (Agee 1993)

Despite this accuracy, tree-ring data lack the ability to record stand-replacing fires and thus in the case of New Zealand it has limited application. The use of fire scars is further hindered by being restricted to the age of the oldest living trees, which in most forests is <500 years (Clark 1997, Pitkanen 2000, Pitkanen *et al.* 2001, Whitlock 2001). This relatively small time window assessable by this application means that understanding the pattern of fire at fine temporal and spatial scales is limited in humid regions, due to long periods between individual fires, i.e. the elapsed time since the last fire may exceed the ages of trees (Gavin *et al.* 2003). Furthermore, results obtained from scars only give a conservative estimate of fire frequency as some fires will not form detectable scars (Lorimer 1984).

1.5.2 Pollen

Unlike the above methodology, pollen analysis is not restricted to the age of the current vegetation (Umbanhowar and McGrath 1998), making it possible to study how fire regimes respond to major changes in climate and vegetation over a much more extended period of time than the maximum lifespan of trees. i.e. over many thousands of years (Whitlock *et al.* 1994). Charcoal peaks in Switzland were preceded by pollen types indicating human activity (Tinner *et al.* 1999). This cannot be done in the case of New Zealand as Polynesian food items are predominantly tubers and thus rarely disperse pollen (McGlone 1989, Stevenson *et al.* 2001), therefore interpretation of Māori impact is usually based on a sudden shift in the rate of vegetation change (Stevenson *et al.* 2001). Mcglone (1983, 1989) and Newnham *et al.* (1998b) demonstrated that certain pollen species are useful indicators of fire, in particular (*Pteridium esculentum*) abundance, indicate the frequency and intensity of fires. Likewise Lintott and Burrows (1973) detected an abrupt decline in *Nothofagus* which corresponded with a sharp rise in Poaceae and Cyperaceae. *Leptospermum* pollen that had previously only been present in very low levels reached a peak at this time. These changes represent the widespread clearance of forest by fire during human settlement of New Zealand (Lintott and Burrows 1973, Sugita *et al.* 1994). Although it has been clearly shown that pollen species can detect fire disturbance, not all changes are the result of fire.

The chronology of pollen in sediments is based on radiometric dating (Laird and Campbell 2000), except in a few cases where the lakes have annually laminated (varved) sediments (Whitlock 2001). Dating methods are needed due to different rates in sedimentation or peat growth which determines the temporal resolution of each sample (Whitlock 2001). Due to the imprecise nature of radiocarbon dating, it is not possible to get the same temporal precision of a tree-ring record (Niklasson and Granstrom 1998) and in most cases the chronology is not accurate enough to trace a specific fire event at several sites within a region (Whitlock 2001) due to the huge distance that mobile pollen can travel. An annual or decadal temporal resolution may be possible, although a single sample may span 100 years or more, and thus sample size may have to be adjusted accordingly to reduce the probability of several fire events representing one spike (Klarqvist *et al.* 2001a, Whitlock 2001).

Errors in the radiocarbon dating methods are proportionately large and limit the effectiveness of the method when restricted to a short prehistory such as in New Zealand (McFadgen 1982). McFadgen (1982) found that a radiocarbon date's 95% confidence interval was 140 years, i.e. almost 20% of the duration of settlement in New Zealand. Despite this imprecision, radiocarbon dating is accepted with enthusiasm throughout the world, including New Zealand (McFadgen 1982, Brandova *et al.* 1999, Holdaway *et al.* 2002, Boaretto *et al.* 2003).

The exact resolution of pollen analysis of bog cores is largely determined by the balance between net primary production and decay which is influenced by hydrology and nutrient supply (Dobson 1977, Kuhry and Vitt 1996, Shearer 1997, Klarqvist *et al.* 2001a). Thus changes in water run-off, due to changes in long-term climate patterns or vegetation clearance, are important (Latz 1973, Whitlock *et al.* 1994, Mark *et al.* 1995, Enache and Prairie 2000, Bohlin *et al.* 2001, Nilsson *et al.* 2001, Bragg 2002). In North America, soil and water losses after a fire has passed were cited at being 12-31 times greater on burned sites, due to lower infiltration rates and decreased water absorption, due to hydrophobic conditions destroying surface layer or reducing evapo-transpiration (Ahlgren and Ahlgren 1960, Enache and Prairie 2000). High and low levels of moisture affect the rate of decomposition (Meentemeyer 1978). Water is not available to microbes when the moisture content is below 30% and microbes become oxygen-limited when moisture levels rise above 160% humidity (Harmon *et al.* 1986). In between these values, however, moisture and oxygen levels are biologically ideal, resulting in high levels of microbial activity and hence decomposition (Harmon *et al.* 1986). Thus it is not surprising that peat growth is highly variable. Carbon accumulation rate in Finnish mires varied between 3 and $89 gCm^{-2}\ yr^{-1}$, which varies according to hydrological conditions of the mire (Tolonen and Turunen 1996). Low rates of decay are argued to be the main cause of peat formation rather than high net primary production (Kuhry and Vitt 1996, Bohlin *et al.* 2001, Klarqvist 2001, Klarqvist *et al.* 2001b, 2001a).

1.5.3 Charcoal

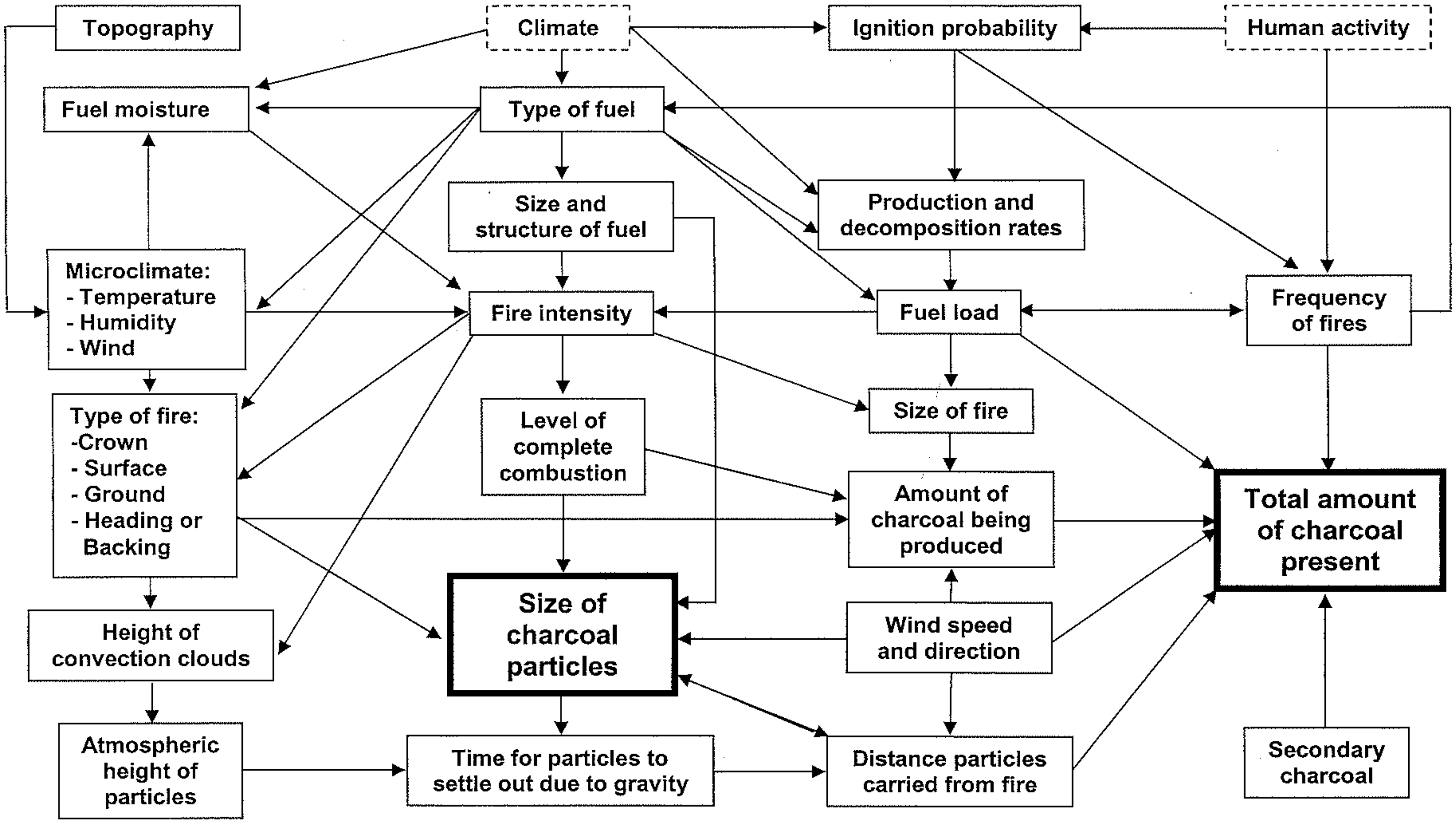
Like pollen, charcoal analysis (typically in bogs) allows one to study the influence of fire well past the age of the oldest living trees (Niklasson and Granstrom 1998, Umbanhowar and McGrath 1998, Pitkanen *et al.* 1999), although it also has the same difficulties with chronology, previously discussed.

1.6 Charcoal complexity

Iversen (1941) first quantified charcoal and drew conclusions about fire history and human settlement. However, it was not until the 1960's that others followed him (Clark 1982). It is now the most common means of examining fire history and pursuing questions of anthropogenic effects on fire regimes (Clark 1982, Patterson *et al.* 1987, MacDonald *et al.* 1991, Rhodes 1998, Umbanhowar and McGrath 1998, Edwards *et al.* 2000, Mooney and Radford 2001).

Complex interactions determine both the amount and size of charcoal particles in bog deposits (Patterson *et al.* 1987, Clark *et al.* 1998, Innes and Simmons 2000, Ohlson and Tryterud 2000, Gardner and Whitlock 2001) (Fig.1.12). The amount and size of charcoal produced in any one fire may vary for several reasons including fire size, amount and type of fuel burned, relative humidity, fuel flammability, fire intensity. wind direction during the burn, frequency of fires, and whether the fire was a heading or backing fire (Clark and Patterson 1994, Larsen and Macdonald 1998, Mohr *et al.* 2000, Gardner and Whitlock 2001). For example, a backing fire that burned under high humidity and low wind conditions would more likely produce large amounts of macroscopic charcoal, while a high intensity fire that burned under hot, dry and windy conditions would more likely combust fuel very efficiently and produce small amounts of fine charcoal particles (Larsen and Macdonald 1998, Camill *et al.* 2003). Not all local fires cause a peak in macroscopic charcoal (CHAR) (Clark 1990), and some peaks in macroscopic CHAR reflect regional fires (Patterson *et al.* 1987, MacDonald *et al.* 1991). Thus, there is no straightforward correlation between the magnitude of charcoal peaks and the size of the source fire (Pitkanen *et al.* 1999, Innes and Simmons 2000).

Fig. 1.12. Amount and size of charcoal present; dashed boxes signify the impoprtance of climate and human activity in influencing the fire regime; bold boxes highlight the fact that differences in, size and amount of charcoal can be due to a variety of interactions.



This means that it is essential to identify a few assumptions when deciding on an appropriate methodology and interpreting the obtained results.

1. Bog sedimentary layers with charcoal abundance above some background amount are evidence of a fire event in the past.
2. Most sedimentary charcoal is from primary fallout during or shortly after a fire; secondary or redeposited charcoal is a relatively minor component.
3. Large particles are not transported long distances and thus are indicative of local fires.
4. Charcoal fragments can be reliably extracted and quantified from the sediments using the current techniques of palaeoecological research.

(Whitlock and Millspaugh 1996, Blackford 2000b, 2000a)

1.6.1 Charcoal fluctuations

Due to secondary dispersal after the fire event, over land and water, there is a continuous influx of charcoal, known as "background charcoal" or "secondary charcoal". This charcoal is not considered as an indicator of fire activity. Influxes over and above this background charcoal are considered as a fire episode (Clark and Royall 1996). Some charcoal peaks may represent more than one fire. In this study, the term 'fire episode' rather than 'fire' is used to emphasize that each peak may represent one or more fires. A fire episode is defined as one or more fires within the time interval represented by the sedimentary sample increment (Long *et al.* 1998, Huber and Markgraf 2003).

Charcoal is a relatively inert substance (Scott and Jones 1991). It is not altered by any natural chemical or biochemical processes occurring at low temperatures and, once created, it has the potential to be preserved in the deposits it settles in (Goldberg 1985, Garstang *et al.* 1994, Suman *et al.* 1994, Nichols *et al.* 2000). Thus carbonaceous particles are nearly ubiquitous in sedimentary environments, found in lake sediments, peat, and soil throughout the world, providing evidence of past combustion (Molloy *et al.* 1963, Swain 1973, Zackrisson 1977, Goldberg 1985, Patterson *et al.* 1987, Clark 1988d, 1988e, 1988c, MacDonald *et al.* 1991, Anderson and Smith 1994, Bradbury *et al.* 1994, Clark and Royall 1995, Clark and Hussey 1996, Clark and Royall 1996, Tolonen and Turunen 1996, Chambers *et al.* 1997a, Chambers *et al.* 1997b, Clark *et al.* 1998, Long *et al.* 1998, Edwards and Whittington 2000, Edwards *et al.* 2000, Innes and Simmons 2000, Laird and Campbell 2000, Pitkanen *et al.* 2001, Whitlock 2001). This fragile nature of charcoal means that non-woody vegetation is often too fragile to survive charcoalification and subsequent mechanical damage (Figueiral and Mosbrugger 2000).

Charcoal is a proxy indicator of fire as partial combustion (or pyrolysis) results in the formation of charcoal at temperatures 280^{0} to 500^{o}C (Umbanhowar and McGrath 1998, Nichols *et al.* 2000). Certainly, if we use charcoal-like fusain in the fossil records as an indicator of fire, it is of paramount importance that we can state beyond reasonable doubt that the fossil material is true charcoal, i.e. the end product of pyrolysis.

Charcoal is usually characterized by either the spherical bodies without structure, or the particles with some original plant structure preserved (Yunli *et al.* 2001). It is generally identified on the basis of being angular, uniformly black and opaque (Fig 1.13.) (Goldberg 1985, Clark *et al.* 1989, Robinson *et al.* 1994).

1.6.2 Primary fallout

The majority of charcoal accumulation, predominantly less than 50μm in diameter (Clark and Royall 1995, Mooney and Radford 2001), occurs during a fire, or shortly after, through primary fallout, with only 10% of microscopic charcoal originating from regional sources (Innes and Simmons 2000). This is particularly relevant in the case of peat bogs because "secondary charcoal distribution" is insignificant in peat cores as peat fibres filter out secondary charcoal close to the vegetation edge or stream entry to the bog, preventing secondary charcoal reaching the core site i.e. no background charcoal. Since predominantly all of the charcoal present originated from primary fallout, scientists can use different size proportions to signify the proximity of the fire due to different terminal velocity, determining the particles' atmospheric time, time to settle out of the atmosphere, which influences the possible horizontal distance that they can travel.

Figure 1.13 Assortment of large charcoal particles

1.6.3 Atmospheric time

As thermal buoyancy is lost, particles increasingly begin to settle to the ground at a rate which is highly sensitive to particle size (Clark and Patterson 1994). This relationship occurs because the effects of gravity rapidly increase with increased particle size, resulting in the large particles preferentially falling out sooner than the smaller particles. Particles of 50 -1000 μm diameter settle at rate of 1-100 cm/s, resulting in a short atmospheric life (Clark *et al.* 1996). These larger particles are not transported very far from the edge of the fire, at most tens of kilometres (Laird and Campbell 2000). Studies have also indicated that large particles not only have a faster settling velocity (Patterson *et al.* 1987, Clark 1988c) but rarely enter suspension e.g.(Anderson *et al.* 1986, Clark 1988b, 1990, Cofer *et al.* 1994, Garstang *et al.* 1994, Millspaugh and Whitlock 1995, Clark and Hussey 1996, Clark and Royall 1996, Whitlock and Millspaugh 1996, Clark *et al.* 1998, Long *et al.* 1998, Pitkanen *et al.* 1999, Blackford 2000a, Laird and Campbell 2000, Gardner and Whitlock 2001, Antonio *et al.* 2002). Therefore, the presence of large charcoal particles is indisputable evidence of local or insitu fires (Clark 1988c, Birks 1994, Novakov *et al.* 1994, Clark *et al.* 1998, Ohlson and Tryterud 2000, Mooney and Radford 2001, Pitkanen *et al.* 2001). Thus the trend in recent studies is to concentrate on macroscopic charcoal particles, >100μm in length, as this size range gives a more accurate picture of the local fire patterns (Clark 1988d, 1988e, MacDonald *et al.* 1991, Millspaugh and Whitlock 1995, Clark and Hussey 1996, Hallett and Walker 2000, Millspaugh *et al.* 2000, Mohr *et al.* 2000, Huber and Markgraf 2003). Regardless of size, the majority of particles settle close to the fire site (Clark 1988c, Clark and Patterson 1994). Results from Ohlson and Tryterud (2000); (Fig.1.14) shows that there is a significant decrease in particle accumulation as you get further away from the edge of the burn area. Thus, although small particles, <50μm, have a regional component, 10% (Schwilk 2003), a large majority of the microscopic charcoal derives from local sources (Anderson *et al.* 1986, Wein *et al.* 1987, Pitkanen *et al.* 1999, Mooney and Radford 2001) .

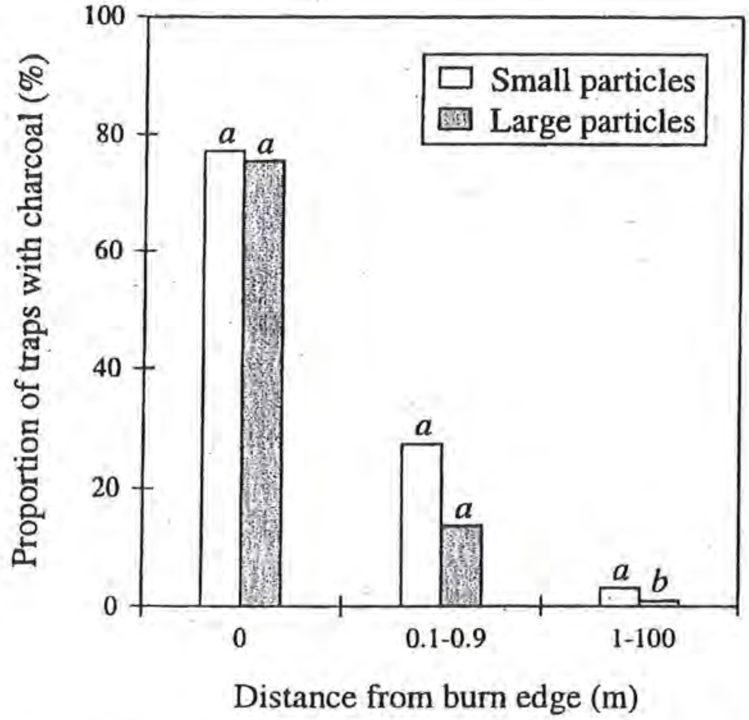


Figure 1.14 Charcoal distribution from the edge of a fire (Ohlson and Tryterud 2000)

Convection currents can carry small particles to high initial altitude (Patterson *et al.* 1987, Clark 1988d, Clark and Royall 1995, Mooney and Radford 2001). Created by the immense heat, these uplifting winds can carry small particle to heights of 10,000 m (Fig 1.15) (Clark

1988c, Fuller 1991, Clark and Patterson 1994, Clark *et al.* 1998, Ohlson and Tryterud 2000). From these heights, combined with the slow settling velocity, these particles can travel great distances. They could theoretically have originated from distant sources hundreds or thousands of kilometres away (Clark 1988e, Garstang *et al.* 1994, Laird and Campbell 2000), with the horizontal distance travelled strongly linked to the fire intensity due to its effect on the size of resultant convection clouds (Clark and Patterson 1994).

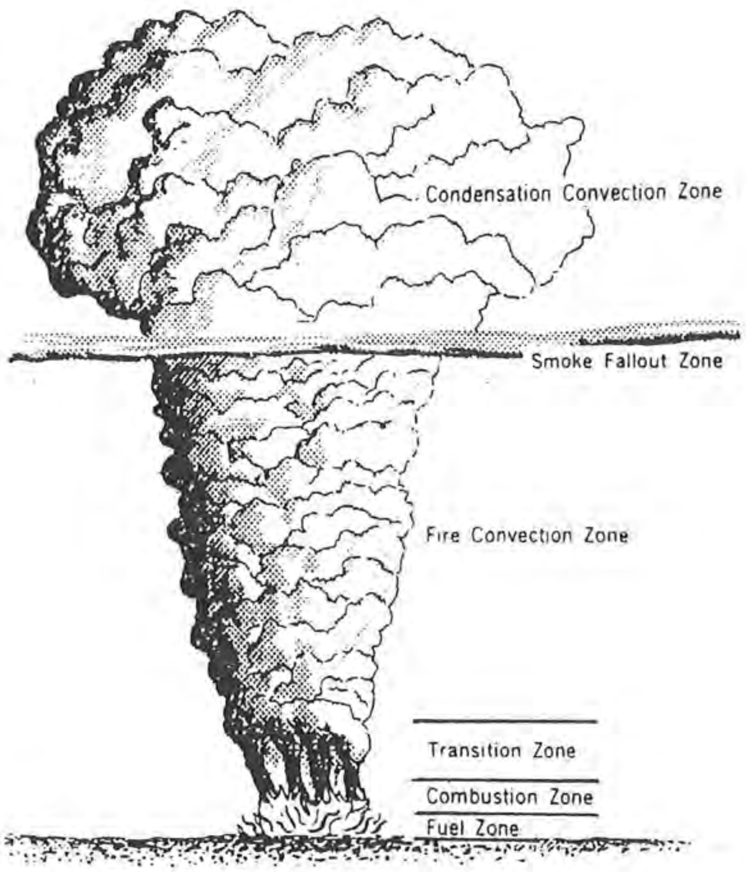


Figure 1.15 Structure of fire induced convection cloud; from (Pyne 1984)

1.6.4 Quantification of charcoal

Various different methodologies have been developed to extract and quantify charcoal particles successfully. These methodologies vary widely and include sieving methods, thin sections, chemical assays, coal petrography techniques, an array of pollen slide counting methods, and mineral magnetism (Patterson *et al.* 1987, Clark 1988e, 1990, Rhodes 1998, Gedye *et al.* 2000, Laird and Campbell 2000). Dependent on the aims of the experiment, careful consideration is needed when choosing an appropriate methodology, as it determines the spatial and temporal resolution of the study via effects on detectability of different sizes

(Clark 1988d, Clark and Hussey 1996, Hallett and Walker 2000, Millspaugh *et al.* 2000, Mohr *et al.* 2000, Huber and Markgraf 2003).

Sieving samples through a set of nested sieves results in distinct peaks in the larger particles, >150μm, due to a low background component, i.e. the absence of charcoal of this size from distant sources (Carcaillet *et al.* 2001b). Sieving techniques also minimise fragmentation, providing care is taken, thus making reconstruction of fire regimes less ambiguous.

Due to time-constraints, pollen and charcoal analyses are often done in conjunction with one another. For example, Rhodes (1998) found that 78% of all palaeoecological studies used pollen slides to determine charcoal concentrations, despite the fact that pollen slide preparation affects the size of individual charcoal particles through the harsh mechanical and chemical processes needed to digest and remove non-pollen organic and inorganic material from the sediment matrix (Rhodes 1998). Despite the robust chemical nature of charcoal, it is physically rather fragile. Small amounts of mechanical manipulation can result in it being crushed into smaller fragments, and so charcoal particles are susceptible to oxidation, degradation and considerable fragmentation during the pollen preparation (Carcaillet *et al.* 2001b), thereby making identification of source of charcoal due to size classes difficult. However, if non-abrasive sample preparation processes are used to minimise fragmentation, the relative distribution of different charcoal size classes from <1μm to >1mm in length (Patterson *et al.* 1987) can give an indication of fire proximity (Anderson *et al.* 1986, MacDonald *et al.* 1991, Innes and Simmons 2000). With this inference, scientists are able to make tentative conclusions about where the charcoal is sourced from, local catchments or adjacent areas (MacDonald *et al.* 1991, Mensing *et al.* 1999, Innes and Simmons 2000).

1.7 Research Rationale

There is a lack of information about, and understanding of, forest fire regimes for most regions of New Zealand before human occupation. Forest ecologists and fire managers require this information to provide a baseline for comparisons with present / post settlement fire regimes. Scientists studying evolutionary history, human settlement impact, or climate variation also need this information (Umbranhowar 1996, Huber and Markgraf 2003).

Despite the seemingly obvious benefits of continuous sampling through time, it appears that studies worldwide have most often chosen more minimal sampling methodologies. That does not enable the identification of every individual local fire event (Clark *et al.* 1996, Whitlock 2001, Wilmshurst *et al.* 2002, Huber and Markgraf 2003). New Zealand is no different. Despite the immense impact that fire is known to have had on New Zealand ecosystems, there are very few high resolution continuous data relating to fire history, making historical interpretation difficult and at best speculative.

Over recent years, contrasting hypotheses to the intermediate model, time of colonization of New Zealand, put forward by Davidson (1984) have emerged. Due to the relatively short prehistory of New Zealand, this variation between dates of settlement is critical, as it affects how we reconstruct the environmental changes due to settlement (Newnham *et al.* 1998a). Thus more detailed studies are needed to help clarify New Zealand's prehistory (Newnham *et al.* 1998a, Newnham *et al.* 1998b).

1.8 Aims

I will use a combination of methods to reconstruct the fire history of the South Island, New Zealand, during the late Holocene.

- To test whether methodology developed overseas is suited for analysing charcoal samples from peat bogs, in New Zealand.
- To determine the most suitable sized particles to unravel New Zealand pre-human and human fire history.
- To test whether climate change controlled intensity and frequency of past fires in the South Island.
- To test whether there are any differences in fire regimes in coastal and inland sites.
- To test for an increase in fire frequency/intensity after Māori and European settlement.
- To test whether there is sequential change north to south and/or coastal/inland during Māori settlement.

1.9 Thesis Structure

Four chapters make up the main body of this thesis. Chapter One (this chapter) introduces wild fire and the considerations that have to be made in order to successfully interpret and disentangle the data. Chapter Two is concerned with assessing the potential of methodologies for detecting historical fire for local use. Chapter Three displays the results and Chapter Four discusses and interprets the results. Chapter Five concludes on the main aims.

Chapter Two
Methodology

This chapter describes the sites, selection, issues and components of the selection and development of methods for detecting past fire regimes based on charcoal particles in New Zealand peat cores. The methods focused on two characteristics: (1) continuous sampling, to ensure that all local regional fire events are recorded, and (2) separation of charcoal from the peat matrix by a process that minimises chemical and physical stress placed on the particles.

2.1 Site Selection Consideration

Charcoal–bearing sites are naturally depositional and thus subject to usual taphonomic constraints. Taphonomic processes influence the distribution and abundance of charcoal in bog and lake cores. In particular, fluvial transport and alluvial reworking of charcoal pieces from surrounding soils can be a major problem, as these particles are not necessarily from a single fire, thus their depositional timing is not necessarily correlated with the time of fire (Scott 2002). Ideal depositional sites for reconstructing fire history from charcoal occurrence are sites at which these taphonomic processes can be excluded or minimized (Scott 2002).

The level of sediment focusing and redistribution in peat bogs is minimal (Wein *et al.* 1987, Bradshaw *et al.* 1994), especially when comparing it to charcoal particles found in lakes (Clark 1988, Edwards and Whittington 2000, Nichols *et al.* 2000). However, peat bogs may be biased towards small particles, as large particles are more typically transported by water and thus are predominantly sieved out at bog edges (Scott *et al.* 2000), unless the fire proximity is very close and thus air-borne large charcoal particles are directly deposited in the bog (Clark 1988).

Sites with aerial deposition are preferred over sites with fluvial/alluvial deposition as aerial deposited sites produce a precise time of fire compared to one that has considerable background noise due to continual input and overlapping of fire signals (Jacobson and Bradshaw 1981, Whitlock and Millspaugh 1996, Laird and Campbell 2000, Gardner and Whitlock 2001, Whitlock 2001). For example studies in Yellowstone National park have shown fluvial and alluvial charcoal deposits on to the bottom of a lake continue several years after the actual fire event and have been known to be still occurring 30 years later (Patterson *et al.* 1987) as a result of continual input from the watershed. This continual input makes the detection of regional fire activity nearly impossible as it is hidden in considerable background noise (Laird and Campbell 2000).

Furthermore, sedimentation processes within a lake control where and when charcoal will accumulate in the deep water sediment (Clark and Royall 1995, Bradbury 1996, Chambers *et al.* 1997). Due to continual redistribution by winds and later by horizontal currents (Bradbury 1996), further mixing creates even more noise, decreasing the definition of the results (Larsen and Macdonald 1998). This movement of particles in horizontal currents is aided by the fact that fine charcoal particles can become suspended above the thermocline and can remain there for substantial periods of time.

Unfortunately peat depth does not directly relate to time, due to uneven rates of growth, both in time and space. This has significant implications, as apparent changes in fire regimes could be the result of compression or stretching of charcoal counts (McGlone and Wilmshurst 2004). Despite this limitation, small peat mires are a favourable medium for the preservation of charcoal due to the absence of the complications of mixing and redistribution (Whitlock *et al.* 1994, Innes and Simmons 2000).

2.2 Study area

New Zealand lies at latitudes $34^{o\ O4'}$S. and $47^{o\ O2'}$S. between the high pressure belt of the subtropics and the low pressure zone of the Southern Ocean (Garnier 1948, 1958, Burrows and Greenland 1979). Because of the influence of the surrounding ocean and its geographical position, New Zealand is subject to cyclones and anticyclones on a regular basis, resulting in a temperate climate with fairly regular rain episodes interspersed with drier periods (Garnier 1958, Sinclair 1996).

Seasonal precipitation results in the northern and central areas of New Zealand receiving most of their rain in winter with only marginal amounts in summer, whereas for much of the southern part of New Zealand, winter is the season of least rainfall. Due to the influential nature of the Southern Alps, some parts of New Zealand receive significantly less rain than others. No were in New Zealand is this contrast more apparent than between the Fiordland

and central Otago, one of the wettest and driest places in the country (Fig 2.1.). Annual precipitation between sites also varied significantly (Table 2.1)

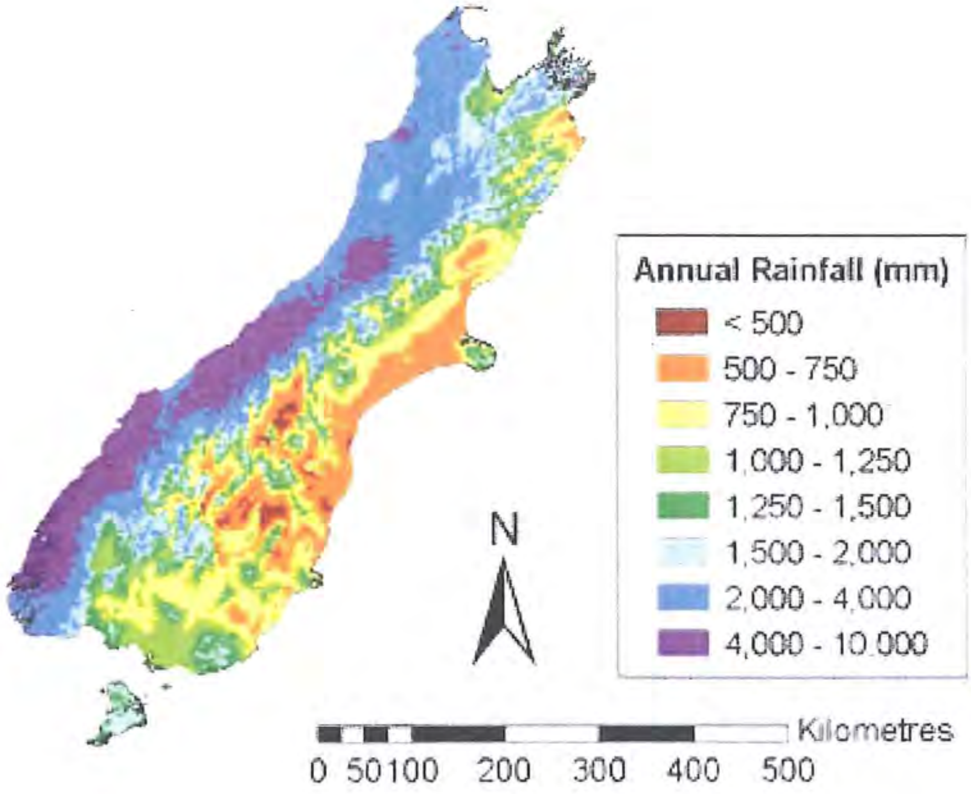


Figure 2.1 Precipitation differences in the South Island. (NIWA 2003).

Table 2.1. Mean annual precipitation from 1890-1969 (Shearer 1973).

Site	Weather station	Reference Number	Annual rain fall (mm)
Travis Swamp	Christchurch	H32561	655 ± 141
Halls Bush	Hororata	H31591	804 ± 150
Glendhu	Lawrence	I59961	746 ± 114
Pomahaka	Roxburgh	I59531	506 ± 84

By world standards, lightning strikes are not common in New Zealand and the ones that do occur are usually associated with moderate to heavy rain (Tomlinson 1976), greatly reducing the chances of fire (Ogden *et al.* 1998) The probability of lightning strikes is also much lower in low-lying areas (Romme and Knight 1981).

In this study four cores were examined, Travis Swamp, Halls Bush, Glendhu and Pomahaka (Fig 2.2). This selection was chosen to enable a direct contrast within and between two climatically different regions, Otago and Canterbury, to identify the importance of climate in local fire regimes. It also enables geographical trends and differences between inland and coastal sites to be detected as a result of colonisation. Radiocarbon dates were used to determine the chronology of the core and to determine when deforestation occurred at each individual site, thus also determining whether movement was predominantly down the coast and then subsequently inland, or if the same event simultaneously occurred throughout the South Island.

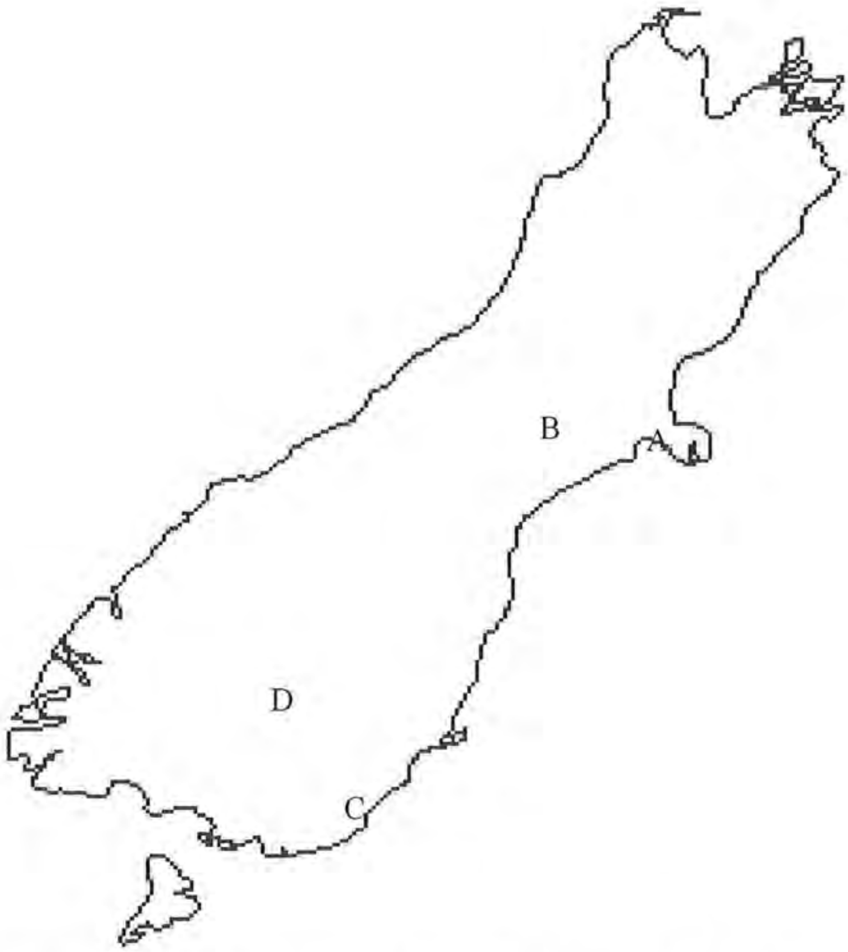


Figure 2.2 Site Location: (A) Travis Swamp, (B) Halls Bush, (C) Glendhu, (D) Pomahaka (McGlone *et al.* 1997, McGlone and Wilmshurst 1999, McGlone 2001)

Zones previously determined by McGlone and Bathgate (1983) (Table 1.3) were used to separate out different periods so that comparisons could be drawn with associated to climatic shifts and dominant vegetation type. An additional zone was added to, at approximately 3000 years b.p which indicated a sudden advance of both *Nothofagus menziesii* and *Nothofagus* subg. *fuscospora* (McGlone *et al.* 1997, McGlone and Wilmshurst 1999, McGlone 2001).

	Yrs b.p	Zone
European arrival	100	2
Polynesian arrival	700	1a
Pre Polynesian 1	3000	1b
Pre Polynesian 2	4000	1c

2.3 Laboratory procedure

Minimize processing so that charcoal breaking is minimal
(Mooney and Radford 2001)

The proposed method draws heavily on those described by Mooney and Radford (2001) and Long *et al.* (1998). It involves carefully dispersing a volumetric sample of sediment through a set of nested sieves of mesh sizes 250μm 125μm and 63μm, followed by the use of digital photography and image analysis programmes to count charcoal particles.

2.3.1 Sampling Techniques

All of the cores examined in this study had previously been collected for pollen analysis by a research team at Landcare Research, Lincoln (McGlone and Wilmshurst 1999, McGlone 2001). Overlapping sediment cores were collected from the centre of each bog. Immediately after extraction, each core was wrapped in polythene and transported to the laboratory where cores were stored, being placed horizontally in a temperature controlled room at 5^0C to prevent samples from drying out.

Each segment of the core was laid down alongside a tape-measure, on a clean bench and carefully unwrapped. Previously sampled points were identified and the core was adjusted to ensure that the points lined up with their corresponding depths, thus ensuring that direct comparisons could then be made between previously recorded data. This resulted in the 0cm part of the sample lining up at the top of the core as it should have. Loose material was then removed before any sampling occurred due to the risk of contamination.

Continuous sampling of the entire length of each core, at 1 cm intervals, followed the methods of Huber and Markgraf (2003) who modified Millspaugh and Whitlock's (1995) methods for compatibility with peat sampling. From each interval, a 2.5 cm^3 sample was extracted and placed into a labelled container, which specified the particular core and depth. In order to prevent contamination, instruments were thoroughly cleaned and wiped between every sample.

2.3.2 Sample preparation

Samples were disaggregated in a 10 % solution of sodium hexametaphosphate ("Calgon") for at least 48 hours (Mooney and Radford 2001). This treatment deflocculates the sediment and breaks up clumps of peat, thereby greatly reducing the need for subsequent mechanical processing. Although this may be adequate in cases with low levels of vegetative matter, it was found that an additional process was required to help make charcoal stand out, thus each sample was soaked in a 5% solution of KOH (Rhodes 1998), for at least 7 days, to bleach and further disaggregate the organic material, intensifying the black charcoal particles and thus aiding the distinction between charcoal and other dark organic matter (Fig. 2.3; (Huber and Markgraf 2003). To reduce the possibility of fragmentation, samples were not heated and no attempt was made to remove all of the organic material, since charcoal could be identified in the presence of some fibrous organic contaminants.

The "Oregon sieving method" developed by Whitlock and Millspaugh (1996) was employed to separate the particles out into three different size classes, >250μm, 125μm-250μm and 63μm-125μm, by gently washing the samples through a set of nested sedimentology sieves under a tap with a flexible hose attached to help direct water. Using minimal water, the sediment was transferred to a labelled container, specifying size class, depth, and core.

Thorough cleaning of sieves between each sample was essential to prevent cross-contamination and KOH crystallising on the sieve mesh.

(a)

(b)

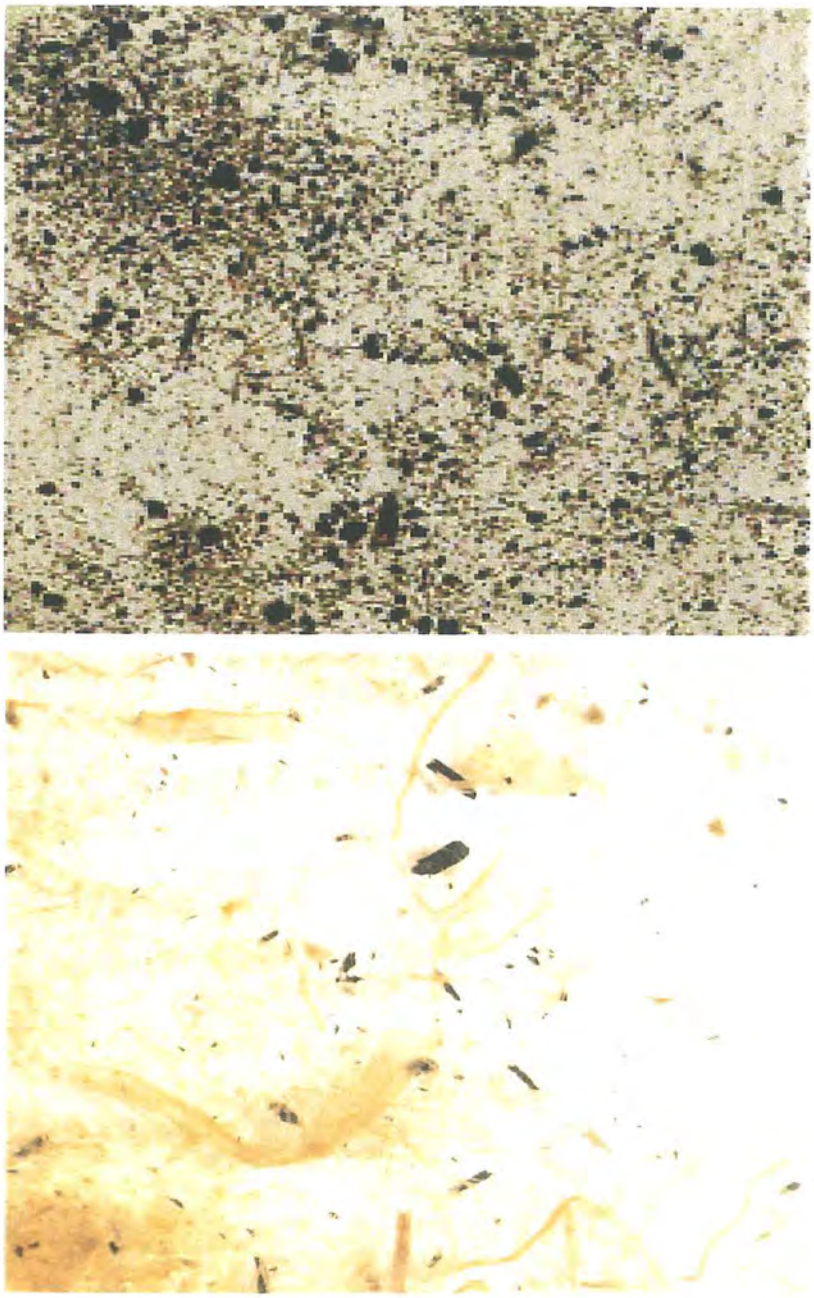


Figure 2.3. Importance of KOH; (a) 250μm sample before KOH (b) after KOH.

2.3.3 Photography

Each sample was carefully washed into a 9 cm diameter Petri dish using as little water as possible. Particles were then evenly distributed throughout the dish by gently shaking the sample side to side.

Photographs were taken with a Nikon DIX digital camera, set up on an adjustable tripod to keep the images to a set size and to minimize movement. An initial photo of a ruler and label (including site name, and size) was taken to allow identification of the core and size of particles of the images that followed. To improve resolution, a Nikon 60 mm f2.8 macro lens was added to the camera. To minimise shading, two studio flashes were set up on either side of the area photographed and photos were taken in a room in which external light could be controlled to counter daily and seasonal differences in light intensity.

The small number of pixels representing the small particles in both the 125μm and 63μm size classes, caused images to appear blurred when the entire Petri dish was in view. Photo size was accordingly reduced to 11.68 by 7.61 mm in order to increase magnification and thus resolution, by attaching an additional lens, Tamron SPAF tele-converter 2x, to the camera, thus markedly improving the resolution, making identification faster and more accurate (Fig. 2.4.)

Despite other studies only utilising one image of the entire Petri dish when analysing >250 μm particles, it was found that the resultant resolution made identification difficult, increasing the probability of error. For this reason two digital images were used to cover the entire Petri dish. Thus the tamron SPAF tele-converter 2x lens was removed and the camera adjusted so that just over half of the Petri dish was in the field of view. This improved both the speed and accuracy of identification considerably (Fig 2.4).

(a)

(b)

(c)

Figure 2.4 Images of individual size classes. (a) >250μm (b) 125-250 μm and (c) 63-125μm

2.3.4 Number of photos required

Since the whole Petri dish was not photographed in the 125-250 μm and 63-125 μm size classes, a representative number of photos was chosen which allowed derived mean abundance to stabilise and the standard error to be reduced to below 10 % (Fig 2.5-2.8). In order to find this number of photos required to obtain an accurate estimate of the charcoal abundance, a series of photos was taken of five randomly selected samples distributed along the entire length of the core, throughout all four cores. Each field of view was achieved by carefully arbitrarily moving the sample (Petri dish) without looking. The Petri dish was adjusted only when the field of view overlapped the edge of the Petri dish. Notice how the mean abundance in all four cores and associated size classes had levelled off by the time ten fields of view had been taken. Even unusually large or small values caused minimal distortion and the mean value quickly returned to its natural path. The standard error (S.E) had also significantly reduced by this point. Although relatively large at the start, it quickly reduced in size by the time ten fields of view had been taken. Due to the mean value flattening off and the S.E being minimal by ten fields of view and the extensive extra time required for marginal improvement of these values, it was deemed counter-productive to increase the number of fields of view. For this reason it was decided that values of the 125 and 63μm size classes would be derived from ten random fields of view.

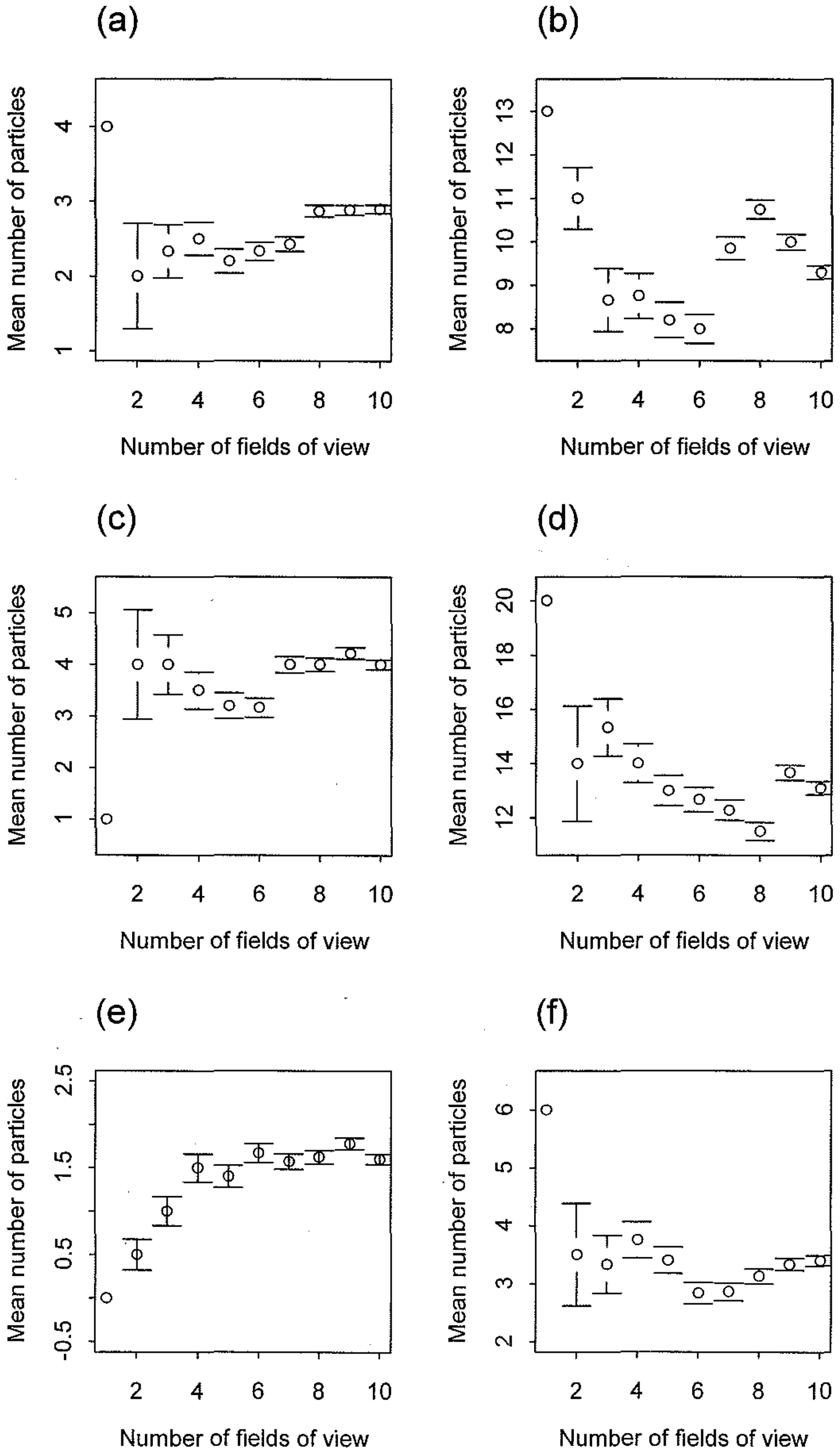


Figure 2.5. Effect of number of photos on estimated charcoal counts for two particle classes at three depths in the Travis Swamp core, (a) 125μm at 44cm depth, (b) 63μm at 44cm depth, (c) 125μm at 20cm depth, (d) 63μm at 20cm depth, (e) 125μm at 8cm depth, and (f) 63μm at 8cm depth. The bars represent the standard error

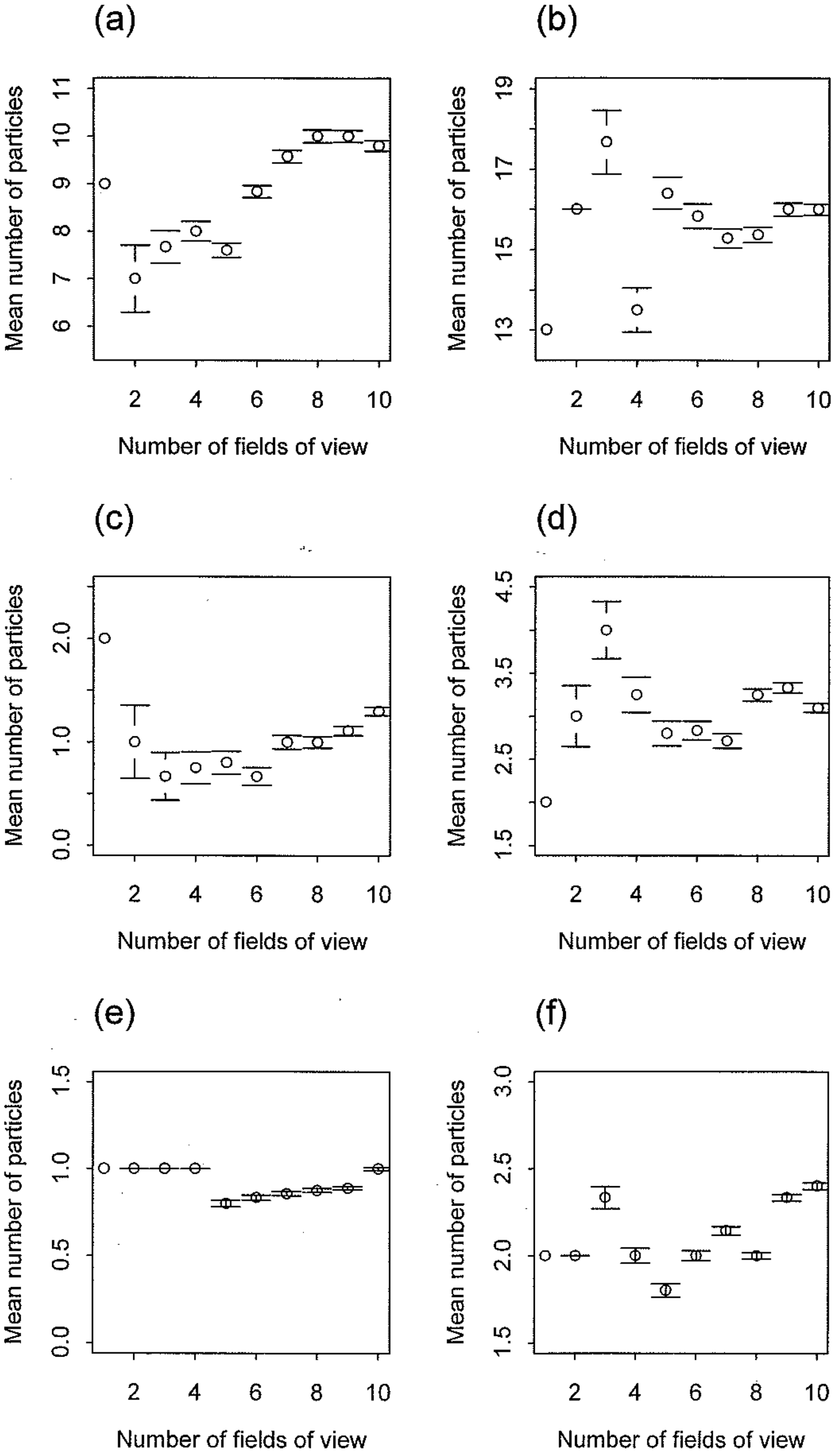


Figure 2.6. Effect of number of photos on estimated charcoal counts for two particle classes at three depths in the Halls Bush core, (a) 125μm at 49cm depth, (b) 63μm at 49cm depth, (c)125μm at 34cm depth, (d) 63μm at 34cm depth, (e) 125μm at 26cm depth, and (f) 63μm at 26cm depth. The bars represent the standard error.

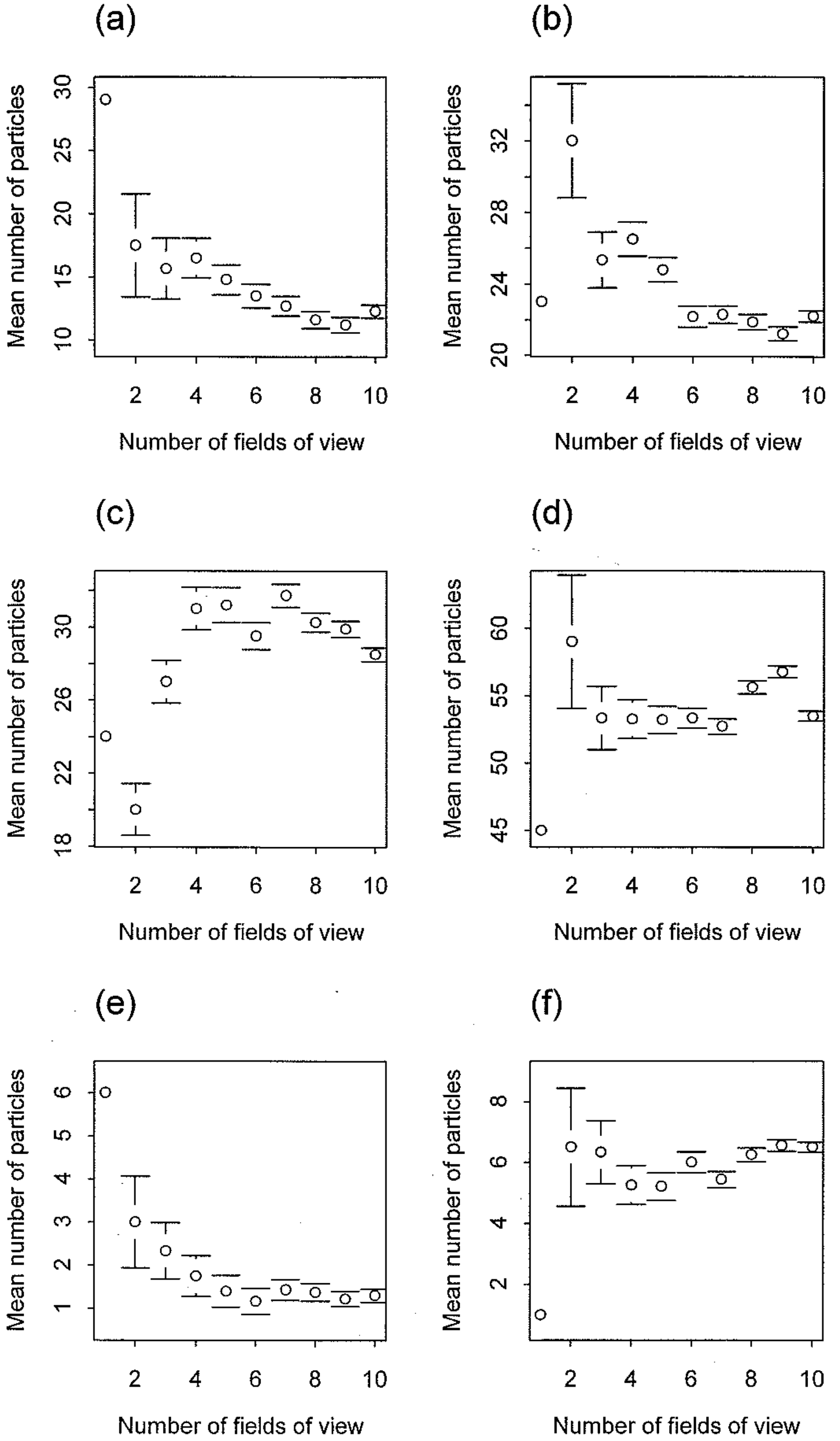


Figure 2.7. Effect of number of photos on estimated charcoal counts for two particle classes at three depths in the Glendhu core, (a) 125μm at 85cm depth, (b) 63μm at 85cm depth, (c) 125μm at 56cm depth, (d) 63μm at 56cm depth, (e) 125μm at 42cm depth, and (f) 63μm at 42cm depth. The bars represent the standard error.

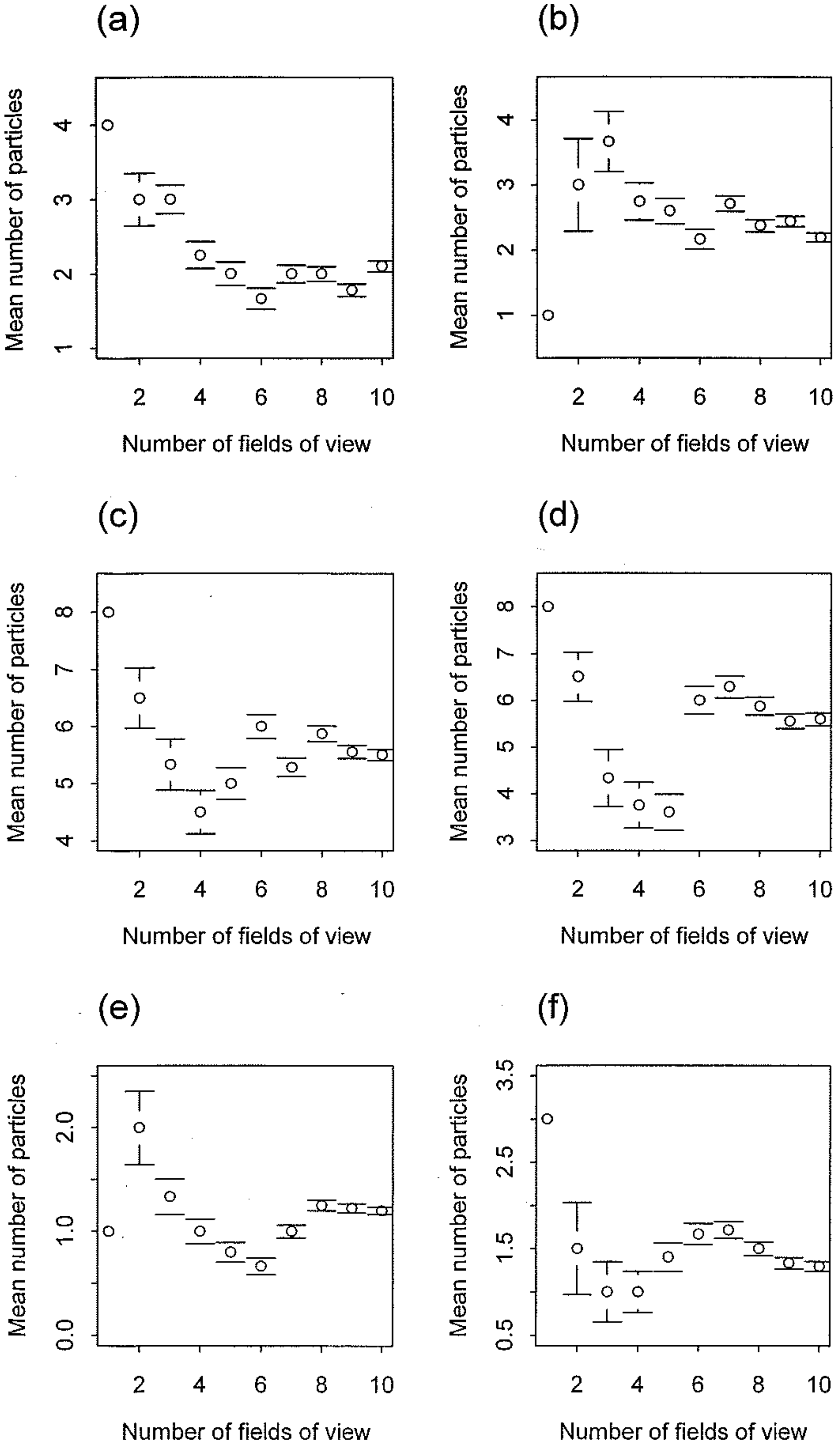


Figure 2.8. Effect of number of photos on estimated charcoal counts for two particle classes at three depths in the Pomahaka core, (a) 125μm at 43cm depth, (b) 63μm at 43cm depth, (c) 125μm at 30cm depth, (d) 63μm at 30cm depth, (e) 125μm at 19cm depth, and (f) 63μm at 19cm depth. The bars represent the standard error

2.3.5 Charcoal analysis

Once the photos were taken and images transferred to a computer, images were renamed specifying the depth. An image analysis program called Image Pro was used to help identify charcoal particles through highlighting every particle that fell within a certain colour range that was previously set. The colour range parameter was adjusted when necessary to ensure that every charcoal particle was identified. Each individual identified particle was then manually checked and kept or discarded accordingly.

An overall indicator of charcoal abundance across all size classes was calculated by using a weighted sum (WS)

$$WS = \sum_{i=1}^{3} W_i C_i$$

where C_i is the count of charcoal particles in size class i and W_i is the weight for that particular size class. The weight was the relative diameter of the geometric midpoint of each size class, with the smallest size class, 63-125 µm, given a weight of 1.00 (ie 63-125 µm 1.00; 125-250 µm, 1.98; > 250 µm, 3.97).

Chapter Three

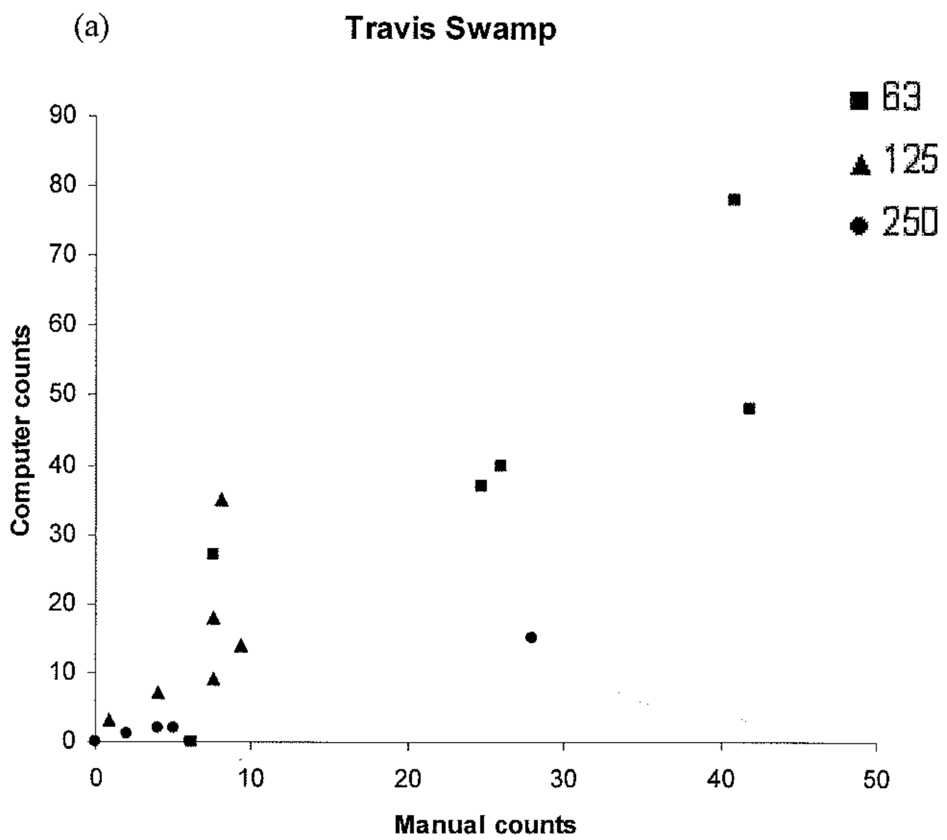
Results

3.1 Validity of methodology

The methodology developed to quantify the amount of charcoal from peat samples in three different size classes, (63-125 µm, 125-250 µm and >250 µm), by using digital imagery and image analysis software resulted in strong correlations occurring between manual counts, Via micro scope, and computer assisted quantities in all three size classes, especially > 250 µm size class (Fig. 3.1). Computer-assisted counts generally underestimate the actual value of charcoal particles, with the exception of Travis Swamp where some values were overestimated in the two smaller size classes. Despite this underestimating of the true value, the computer-assisted counts are highly correlated with the manual counts in all four cores.

Note, after increasing the magnification of the photos of the 250µm size class by using two photos to cover the entire Petri dish (Fig 3.1 c & d), instead of just one, as in (Fig 3.1 a & b), the accuracy of the computer counts greatly increased, with computer counts being a virtual mirror image of the manually obtained values (Fig 3.1 c & d). This close resemblance far exceeds the correlation found between the other two classes.

Charcoal abundance is biased towards the smaller particles (Fig 3.1) with the smallest size class 63-125 µm having significantly more charcoal particles. With every increase in size class, there was a corresponding decrease in number of particles by several orders of magnitudes.



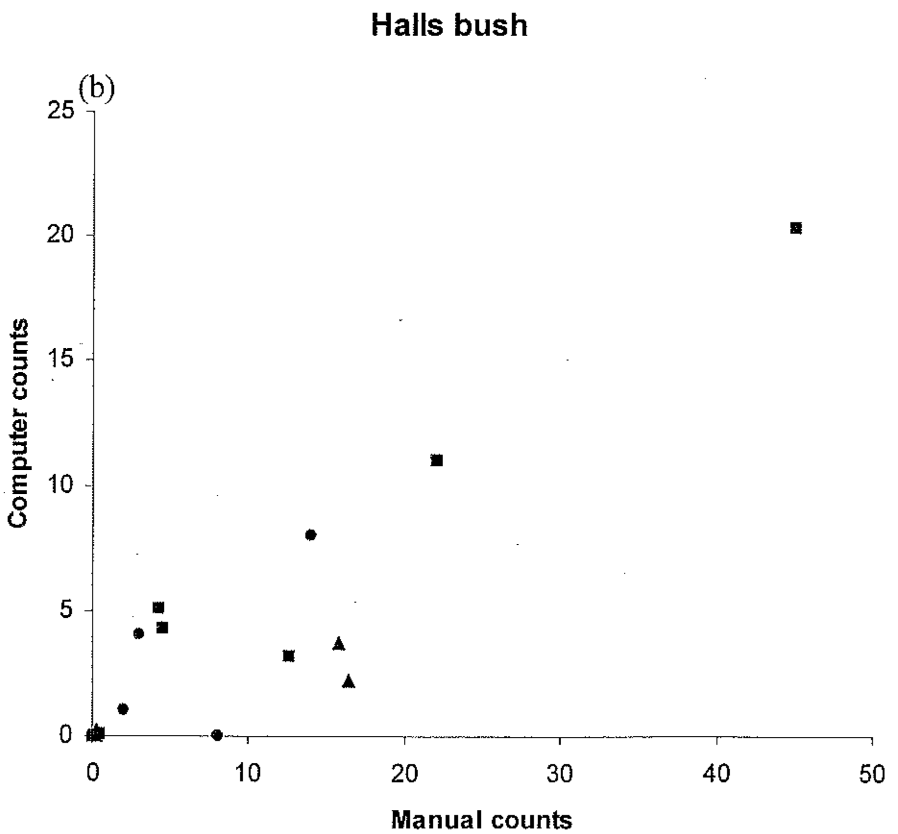
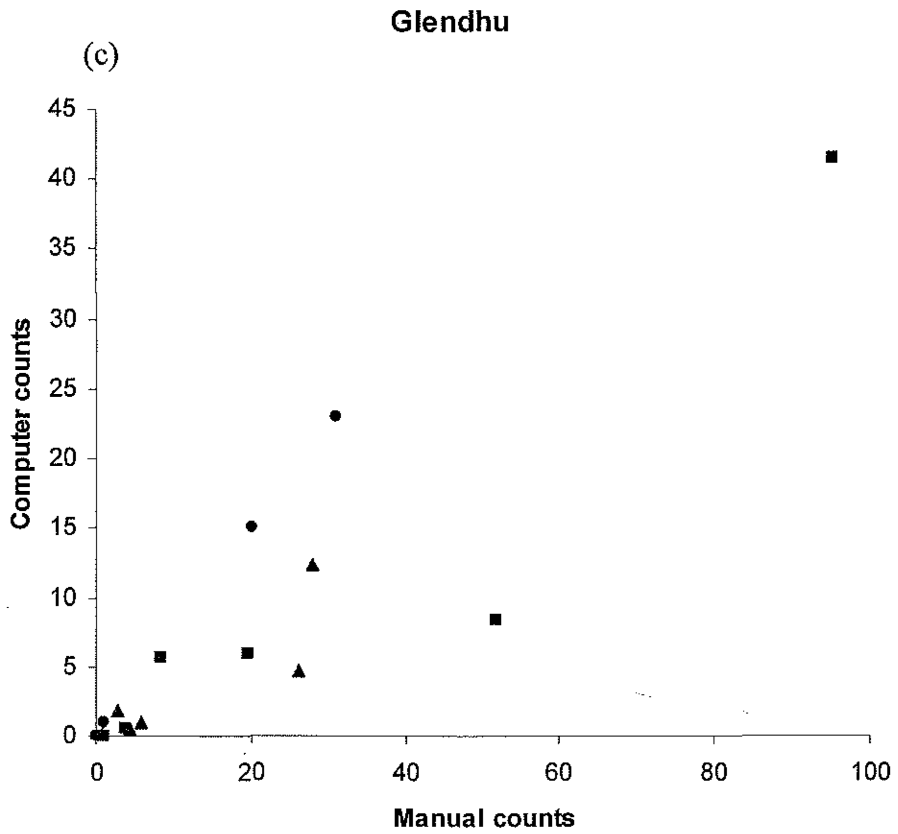


Figure 3.1 Correlation between manual and computer counts. (a) Travis Swamp, (b) Halls Bush, (c) Glendhu and (d) Pomahaka



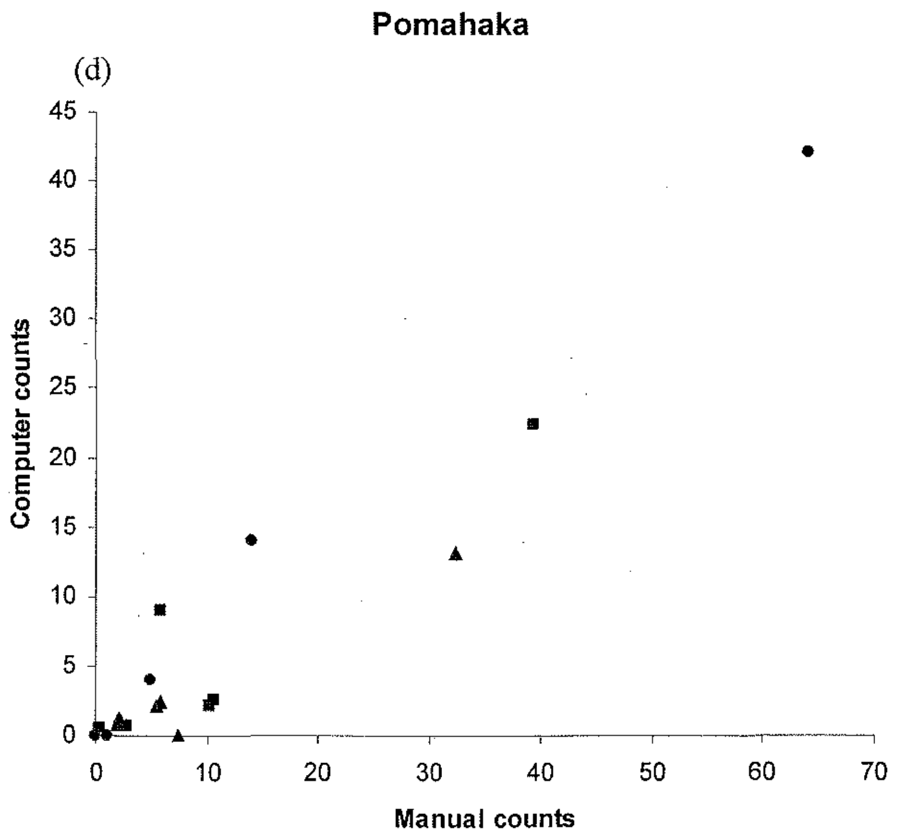


Figure 3.1 continued.

3.2 Radiocarbon dates

Radiocarbon dates associated with each individual site are displayed in Table 3.1. Although the dates obtained from Pomahaka NZA 19668 (40 cm) and 19951 (42 cm) of 807 and 775 years b.p do not follow rank order, they derive from samples only 2 cm apart in the core. The calibrated ages are only 7 years apart and their confidence intervals overlap considerably. For the purposes of interpreting charcoal in the study cores, the mid-point of these two dates has been taken i.e. a calibrated date of 701.5 years b.p. at a depth of 41 cm. The calibrated date of 355 yrs. b.p. from the radiocarbon date NZA 8722 at 63.5 cm in Glendhu Bog is almost certainly a result of contamination from younger carbon. The sample taken was centred where the first signs of charcoal increase and sudden changes in the pollen profile occur, an event associated with Māori settlement and thus almost 400 years younger than other dates from other Otago sites that depict settlement. In line with other South Island studies we have here assumed that the date at this depth is 700 years b.p and this earlier date will be used for calibrations in the remainder of this study, as it represents a more realistic time of deforestation (McGlone and Wilmshurst 1999, McGlone and Wilmshurst 2004).

3.2.1 Peat growth

All cores have a steep negative exponential relationship between growth and age as a result of peat becoming increasingly compressed with depth. Not all periods of deposition follow this expected curve, most noticeably the pre-deforestation values of all four cores. Travis Swamp, Glendhu and Pomahaka cores have higher than expected deposition values at the bottom end of the core (37-113, 70-186 and 82-138 cm depths bands) respectively than would be expected at that depth if deposition was constant, while deposition in the 48-52 cm band at the Halls Bush core has an unusually low value. The relationship between derived age and depth of sample is clearly non-linear. This variation means that a single sample from one part of the core is not necessarily going to represent the same time interval, and thus duration of a fire event for the purpose of the charcoal analysis, as another sample at a different depth within the same core or at the same depth in a different core (Fig 3.2). There is a variation in time intervals between peat deposition rates between locations and sample areas within core zones. This is particularly obvious in the Pomahaka and Halls Bush cores, with the growth rate significantly increasing after the first major charcoal peak after Māori colonisation.

Table 3.1 Radiocarbon dates from South Island Bogs. Calibrations made using INSCAL 4.0 * indicates the beginning of deforestation as assessed by pollen analysis by McGlone and Wilmshurst (1999).

Core	Depth (cm)	^{14}C date (yrs. b.p)	Radiocarbon laboratory reference	Dated material	Calibrated age 68% confidence interval (yrs. B.p.)
Travis Swamp	37 *	722 ± 65	NZA 6649	Peat	645
	113	1341 ± 70	NZA 6355	Peat	1240
Halls Bush	52	2498 ± 58	WK 10900	Peat	2605
	150	4824 ± 68	WK10899	Peat	5560
Glendhu	63.5 *	264 ± 63	NZA 8722	Sedge leaves & seeds	355
	70	1045 ± 70	NZA 6896	Peat	985
	110	2104 ± 71	NZA 6918	Wood	2145
	165	3722 ± 73	NZA 6919	Charcoal	4075
	186	4338 ± 62	NZA 8721	Halocarpus bidwillii leaves & Carex sp. Seeds	4905
	205	8610 ± 110	NZA 6890	Peat	9610
Pomahaka	38	378 ± 74	NZA 7902	Plant fragments	415
	40	807 ± 41	NZA 19668	Peat	705
	42 *	775 ± 40	NZA 19951	Plant fragments	698
	82	4038 ± 42	NZA 19952	Plant fragments	4495
	138	4684 ± 68	NZA 7903	Plant fragments	5445

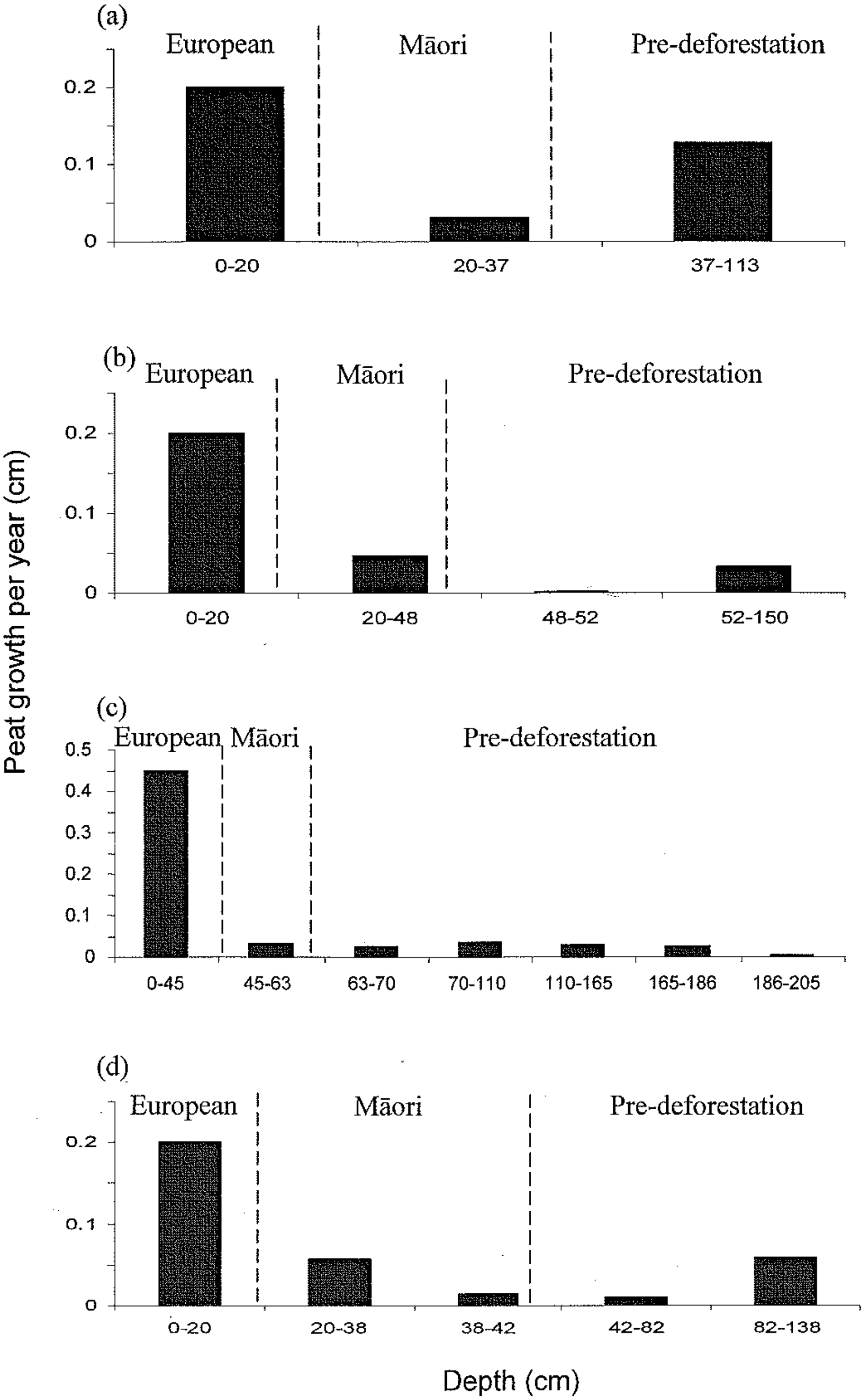


Figure 3.2. Calculated rates of peat deposition. (a) Travis Swamp, (b) Halls Bush, (c) Glendhu and (d) Pomahaka

3.3 Charcoal abundance profiles

Charcoal abundance varied between cores and between zones within cores, but the major change is a large increase between Zones 1c and 2, or immediately prior to this in the case of Travis Swamp (Fig 3.3). This simultaneous change in charcoal input at all sites occurred approximately 700 years b.p, coincident with the short model for Polynesian settlement.

After every major peak, regardless of the zone or core, the abundance of charcoal slowly reduces in subsequent later samples. This is particularly apparent when looking at the first major peak in Zone 2, especially in the Pomahaka site, as peat growth was so slow prior to this peak. After the first peak, individual peaks are sufficiently close together that their charcoal inputs overlap and thus any post-peak decline in charcoal is not as clear. Added to this complexity is a higher level of background charcoal occurring sporadically in between major episodes.

Four major peaks of charcoal occurred in the Travis Swamp core. The first peak occurred at the end of Zone 1c, with a second occurring at the beginning of Zone 2 and the last two peaks occurring in Zone 3. The smaller size class, however, detected up to 11 minor peaks, six of which occurred in Zone 3, four in Zone 2, and one at the end of Zone 1c. One of the major peaks of most interest occurred at the end of Zone 1c, approximately 700 year b.p. This timing at any other site would put it in Zone 2 and would mark the start of deforestation.

Three major peaks occurred in the Halls Bush core, at approximately the same times as the last three major peaks in the Travis core, two occurring in Zone 2 and the third in Zone 3. There were traces of charcoal at the end of Zone 1c and these were the only sign of charcoal in this Zone. Charcoal was largely absent from Zone 1b, apart from the very start where small charcoal particles, 63-125μm, were detected. After 5000 years b.p., small charcoal particles were detected in low quantities but at frequent intervals. These values continued into Zone 1b, but quickly diminished. Before this fire event at approximately 5000 years b.p. however there was no charcoal detected.

There were four major peaks in charcoal in the Glendhu core. One peak occurred at the end of Zone 1a, and consisted of the largest particles to be found anywhere in the core. Two peaks occurred in Zone 2, and the final one in Zone 3. Glendhu was the only core in which charcoal from all size classes occurred in every zone. Although charcoal counts were relatively low in Zone 1b, the only significant absence of charcoal in the Glendhu core occurred at the start of Zone 1a i.e. 4500 yrs. b.p. There is a noticeable dip in charcoal values within all 3 size classes near the end of Zone 2.

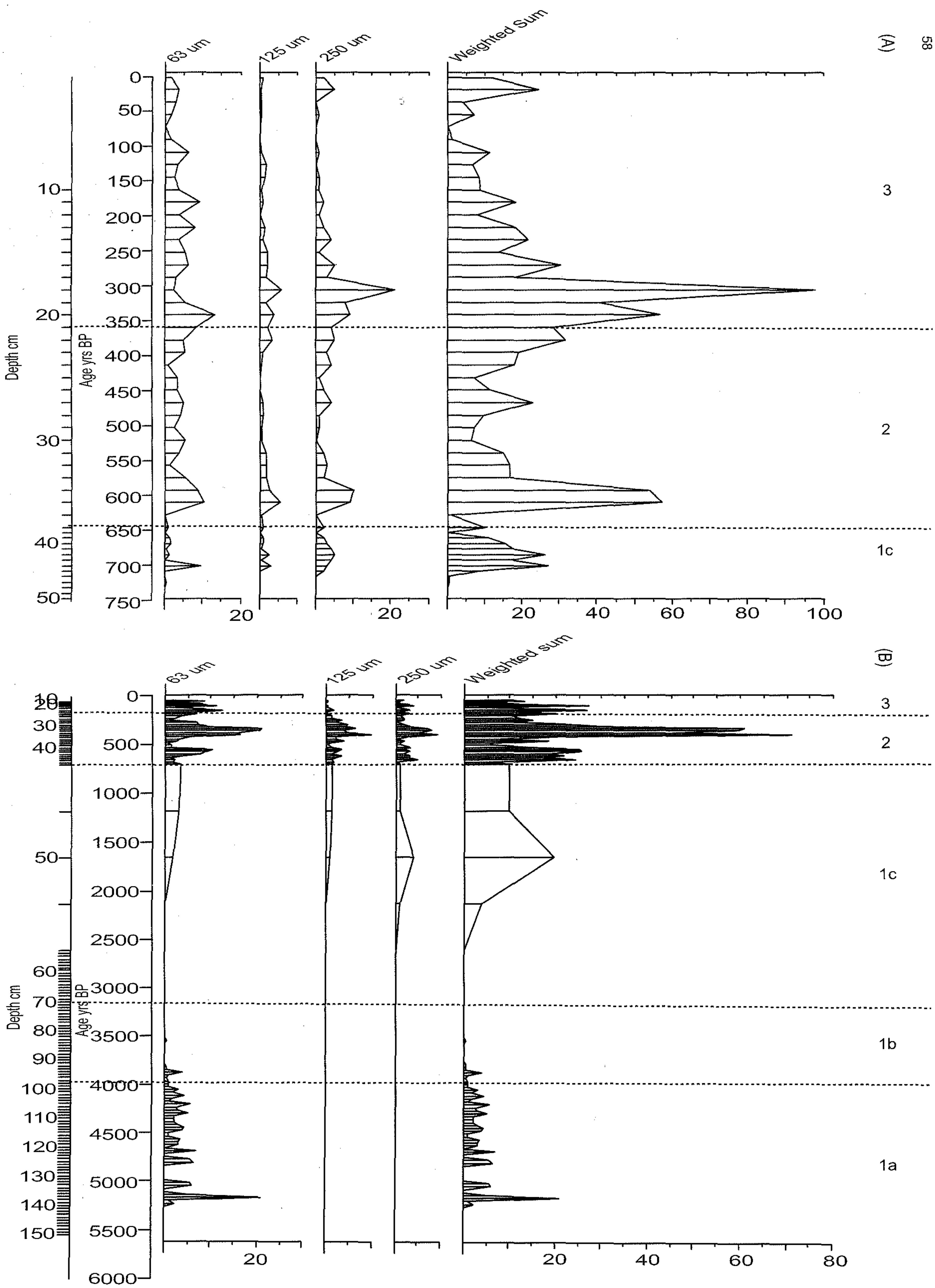
Only one major peak occurred in the Pomahaka core, in the middle of Zone 2. Although charcoal was detected throughout the core, there were no major peaks in any other zones. Unlike the previous two cores in which charcoal values declined at the start of Zone 1b after a peak in late Zone 1a, charcoal levels remained low and relatively constant until near the end of this zone. Large charcoal particles were noticeably absent from Zone 1c. During this same zone, significant quantities of charcoal occurred in only the 63-125 μm class, after which charcoal counts of the two largest size classes abruptly decline at the end of Zone 1b.

Although all zones prior to Zone 2 had significantly less charcoal in all cores, there was variation within these three early zones, with comparatively higher values occurring in Zone 1a, especially in the cases of Halls Bush and Glendhu. Charcoal generally declined between Zone 1a and Zone 2, with almost no charcoal being detected in Zone 1c at any site.

The Pomahaka core had the largest number of large (>250 μm) particles in Zone 2 and the Glendhu core had significantly more intermediate (125-250μm) and small (63-125 μm) particles (Fig. 3.3.) In the other zones, Glendhu had the highest values, closely followed by Pomahaka, with the exception of Zone 3, where Travis Swamp had the second highest values in both the large and intermediate size classes. In nearly all zones, the two Otago cores had higher maximum charcoal abundances. This is especially the case in Zone 2, in which charcoal counts in the > 250 μm class at Otago sites are nearly 100 times greater than the Canterbury counterparts. However this difference is not so prominent in other size classes and zones.

Coastal sites (Fig 3.3 b, d) have slightly more charcoal than the inland sites (Fig. 3.3a, c,) but this is marginal and no real difference between coastal and inland sites was detected.

Figure 3.3 Charcoal abundance. (A) Travis Swamp, (B) Halls Bush, (C) Glendhu and (D) Pomahaka


(A)
Depth cm
Age yrs BP
63 um
125 um
250 um
Weighted Sum
3
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(B)
Depth cm
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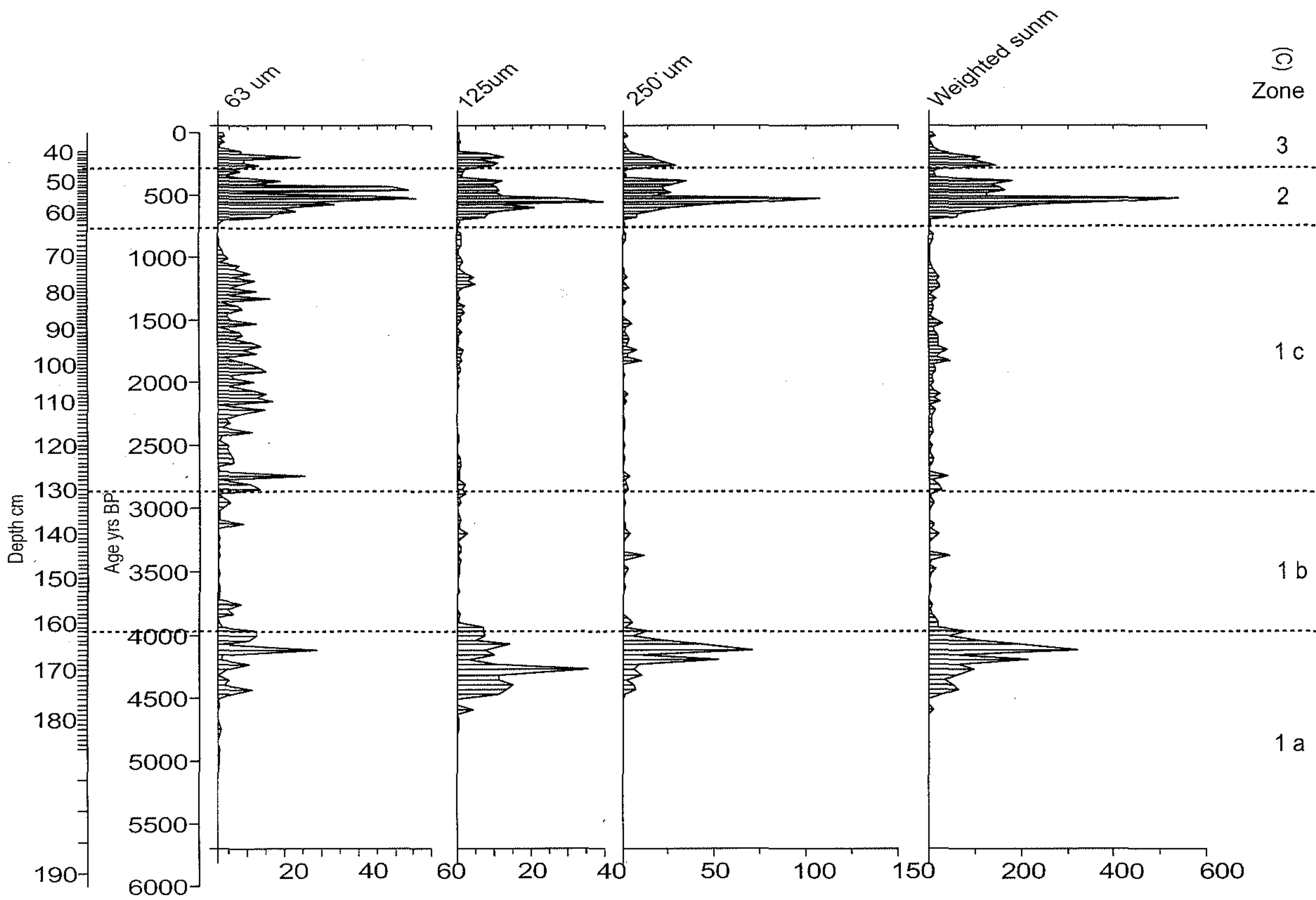
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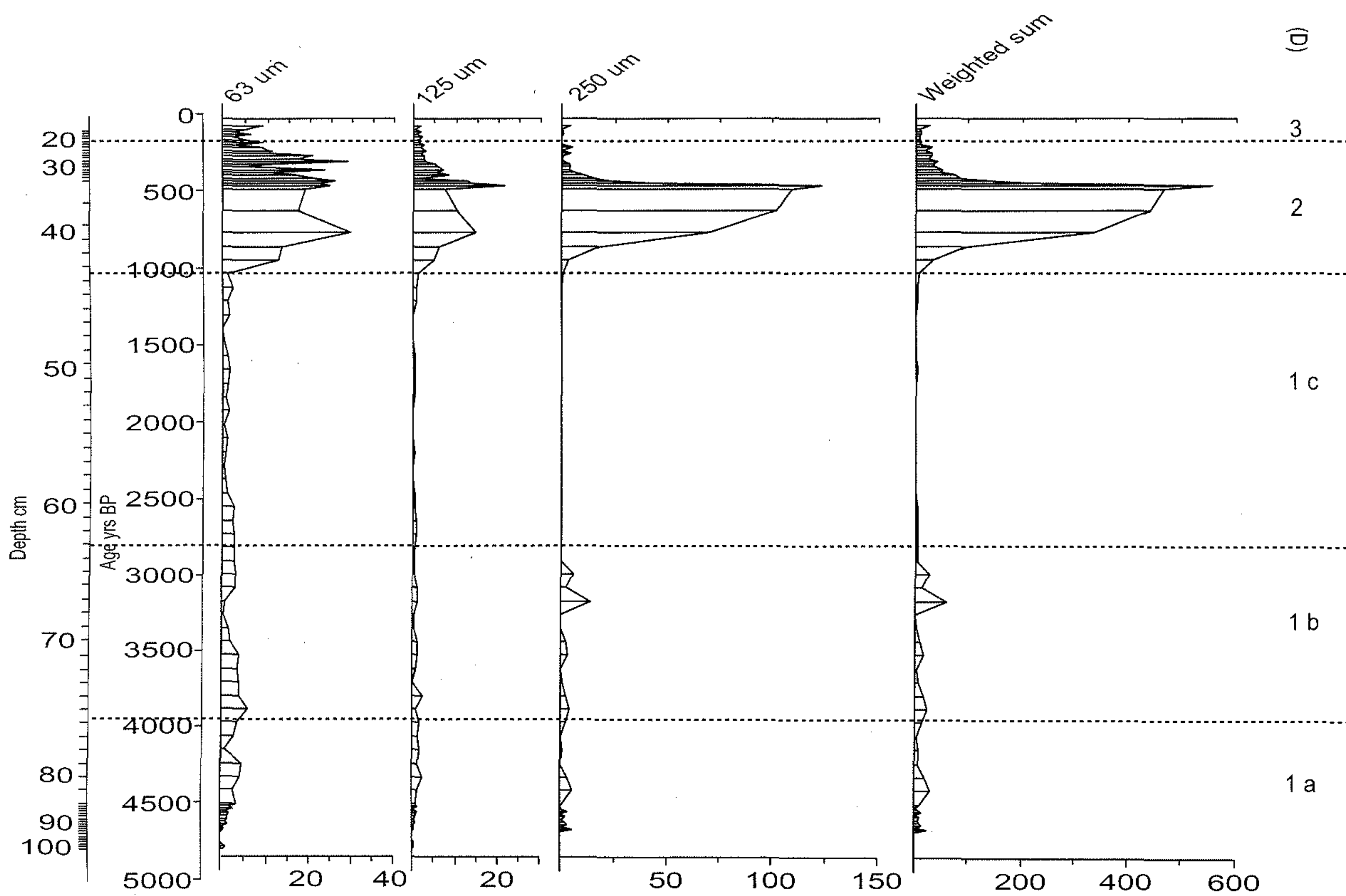
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3.4 Importance of Size

All three particle size classes have similar trends over time in all four cores (Fig. 3.3). When there was an increase in 63-125μm particles, there was a corresponding increase in the larger particle sizes (Fig 3.3), with the highest frequency of large particles coinciding with the highest input of small particles. This is particularly true of the comparison between the 125-250μm and >250μm size classes which were a virtual mirror image of each other.

Despite the overall similarity of depth profiles for the three charcoal size classes, the 63 μm-125 μm size class occasionally showed information absent from the other two size classes. This is most noticeable in the Halls Bush core, where a period of fire activity occurred in that region in Zones 1a and 1b that was only detected by the smallest size class (Fig 3.3). This additional information recorded by the 63-125μm particles occurred to some degree in all four cores. The extent of this additional information, about regional fires more distant from the core's bog, can be demonstrated in the correlation between the > 250 μm particles and 63-125 μm particles which is comparatively weak in most cores and zones (Fig. 3.4). Even when some degree of correlation is apparent, there is a higher proportion of outliers. Correlations of 125-250 μm, with any of the other size classes are significantly higher. Correlations between size classes of particles from Zone 1c (Fig 3.4. j,l, and h) were weaker than comparable correlations in Zones 2 and 3, regardless of size classes compared. Zones 1b and 1a also had weaker correlations than did Zones 2 and 3.

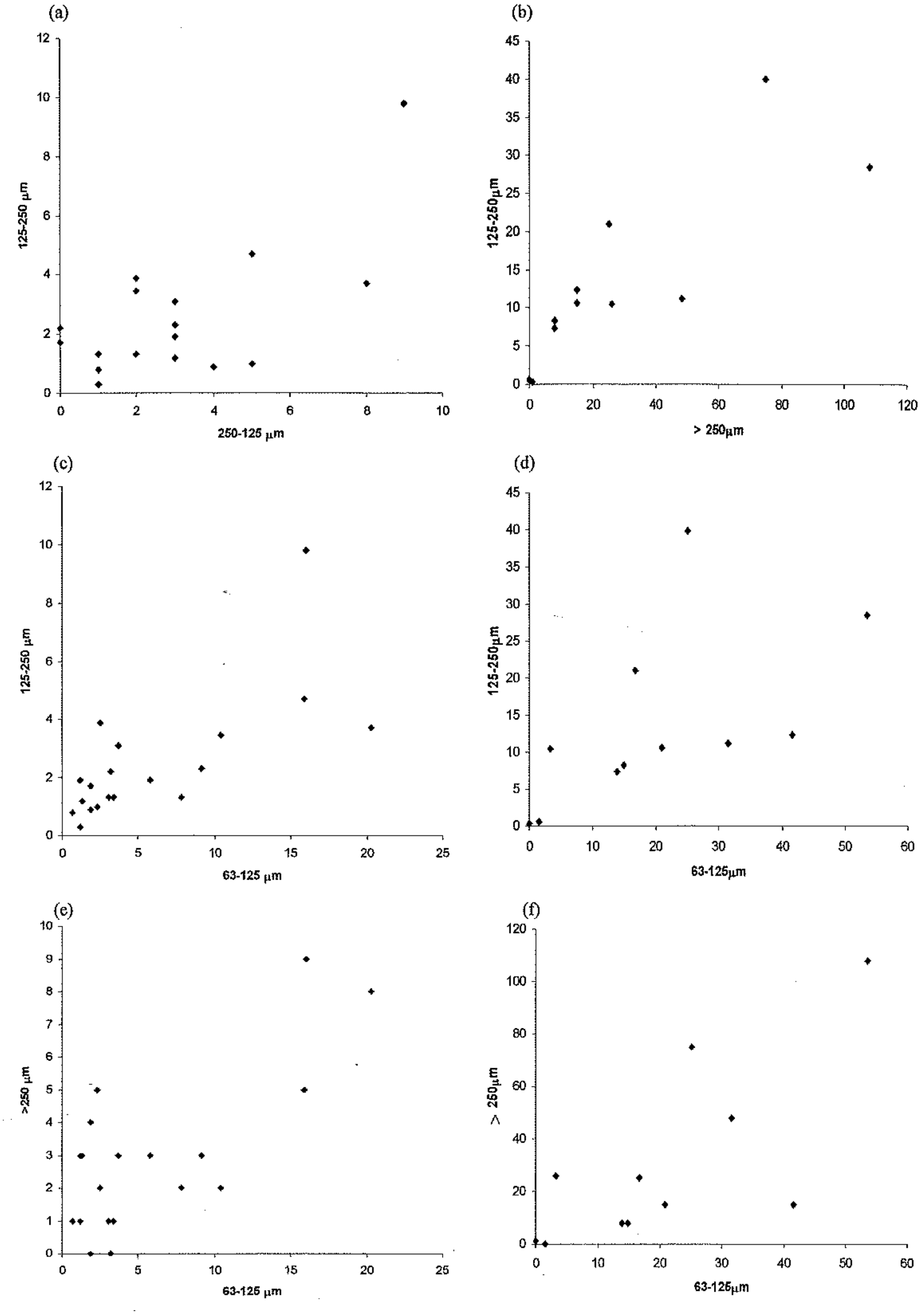


Figure 3.4 Correlations between charcoal counts in different size classes: (a) > 250 µm Halls Bush, Zone 2; (b) > 250 µm Glendhu, Zone 2; (c) 125-250 µm Halls Bush, Zone 2; (d) 125-250 µm Glendhu, Zone 2; (e) 63-125µm Halls Bush, Zone 2 (f) 63-125µm Glendhu, Zone 2. (g) > 250 µm Glendhu, Zone 3; (h) > 250 µm Glendhu, Zone 1c; (i) 125-250 µm Glendhu, Zone 3; (j) 125-250 µm Glendhu, Zone 1c; (k) 63-125µm Glendhu, Zone 3 (l) 63-125µm Glendhu, Zone 1c.

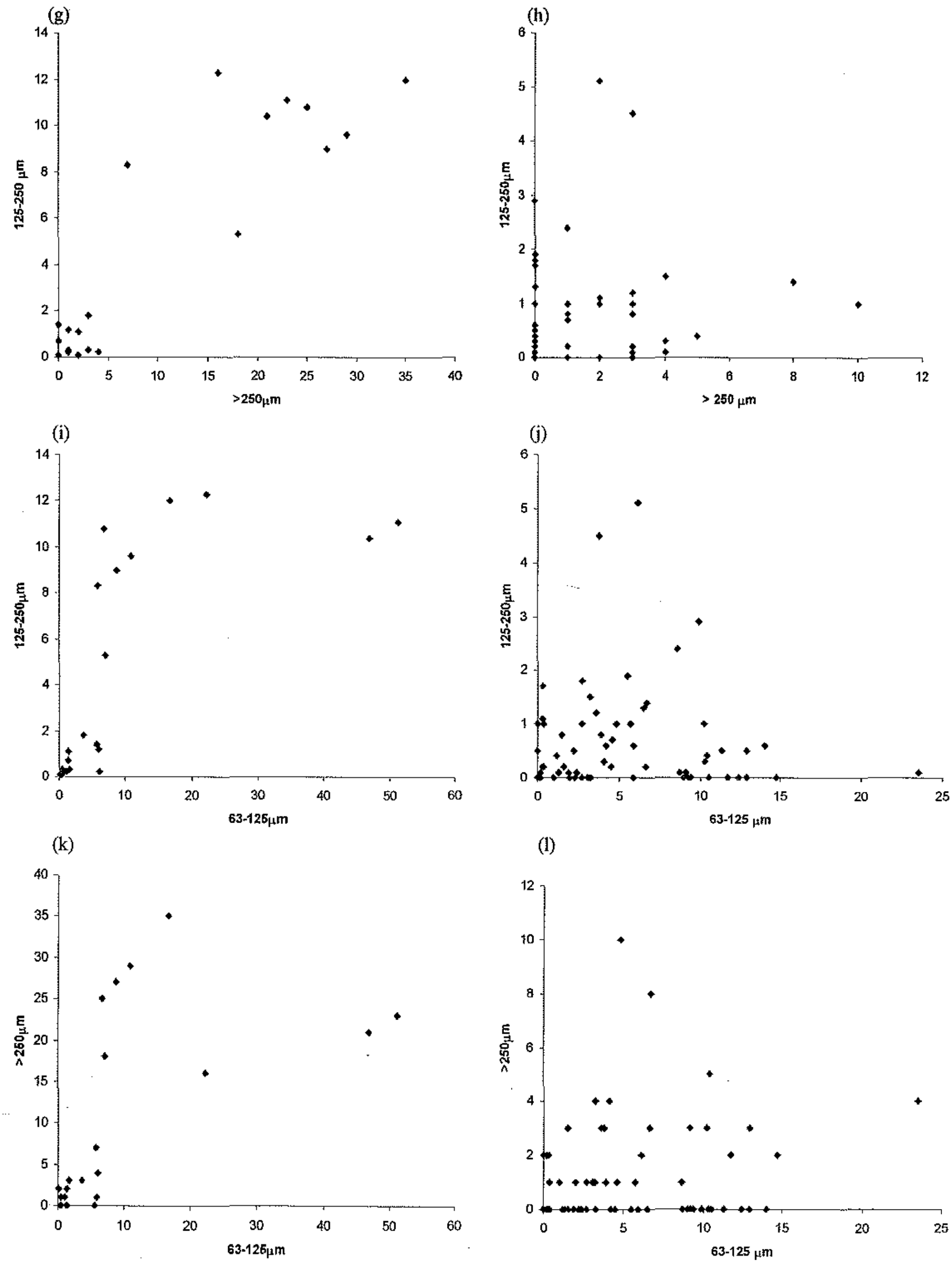


Figure 3.4 continued.

3.5 Correlations between previous pollen profiles

Pollen diagrams presented here for each site (Fig. 3.5) are based on data previously collected from the same cores by McGlone and Wilmshurst (1999), McGlone (2001), McGlone (unpublished) and Wilmshurst (unpublished). Unfortunately, not all pollen and charcoal profiles cover the same time span. The pattern of peaks in all sizes in the study corresponds well with the charcoal peaks in charcoal counts off the pollen slides of the earlier studies from the same cores, and with major changes in pollen composition. The continuous sampling revealed a clearer picture of past fire regimes, enabling more accurate determinations of how charcoal deposits (and thus past fire regimes) fluctuated over time. This is especially important in the two Canterbury sites

3.5.1. Travis Swamp

Nothofagus subg. *Fuscospora*, *Prumnopitys taxifolia,* and Cyperaceae dominated the pollen diagram at the end of Zone 1c. This may be a reflection of their efficient pollen dispersal. While trace levels of *Leptospermum,* Poaceae, and *Dacrydium* pollen species were detected, they did not show any signs of increasing, despite an increase in charcoal near the end of the zone. This influx in charcoal did, however, correspond with a shift in wetland composition around Christchurch, with a decline in *Cyperaceae* abundance and the appearance of *Typha* part way through Zone 1c. Charcoal levels continued to increase into Zone 2 with the corresponding increase in *Typha,* and Poaceae, while all other taxa declined, especially *Nothofagus* subg *Fuscospora*, *Prumnopitys taxifolia,* and Cyperaceae. These changes in composition were comparatively gradual compared with the two Otago sites. The start of Zone 3 saw charcoal levels briefly increase, before sharply declining, simultaneous with the appearance of exotic species. Not until the arrival of exotics in Zone 3 did Poaceae increase in dominance. *Leptospermum* increased briefly in early Zone 3 before declining in the latter half. *Typha* and Cyperaceae, although at relatively low levels compared to earlier zones, remained relatively constant during Zone 3. All other woody taxa declined suddenly at the transition between Zone 2 and 3.

3.5.2 Halls Bush

Throughout Zones 1a, 1b and virtually all of 1c, only the smallest charcoal particles (63-125μm) were detected at low counts. Most of this charcoal was restricted to Zone 1a. *Prumnopitys taxifolia, Coprosma, Leptospermum* type, and *Cyathea* dominated at the start of Zone 1a, with *Prumnopitys taxifolia, Leptospermum* type, Cyperaceae, *Cyathea* and *Blechnum* increasing during this zone. *Aristotelia* appeared briefly in this zone, before disappearing for a prolonged period of time. Levels of charcoal input declined during Zone 1b to the point where no charcoal was detected for most of the end of this zone. *Prumnopitys taxifolia* continue to increase at the start of the zone, before gradually declining. *Leptospermum* and Cyperaceae increased throughout this zone and dominated the pollen profile by the end, while *Cyathea* and *Blechnum* declined. For most of Zone 1c, there was no detectable charcoal, apart from at the very end of the zone where an abrupt increase in charcoal occurred in all three size classes. This zone saw dramatic changes in the pollen profile, with *Nothofagus* subg. *Fuscospora* rising to dominance. Although *Nothofagus* had been present in trace amounts in earlier zones, it wasn't until this point that it was the most common pollen species. *Prumnopitys taxifolia, Coprosma*, Poaceae, *Cyathea,* and *Blechnum* declined to very low values throughout this zone. This zone also marked the beginning of the decline of *Leptospermum,* and Cyperaceae, which up until this point had been steadily increasing. *Myrsine,* although declining slightly at the start of the zone, increased towards the end of the Zone. *Pteridium esculentum* occurred for the first time at the very end of this zone. Zone 2 saw consistently high charcoal values. Despite the apparently high fire regime, *Nothofagus* subg. *Fuscospora* remained relatively high for most of the period before suddenly declining near the end. All other woody taxa declined to very low values, with the exception of *Leptospermum* which, if anything, slightly increased. Ferns and allies appeared to decrease (Fig 3.5). This has been caused by the dominance of *Cyathea* (tree fern) initially due to its shade tolerance and preference for moist conditions. Its dominance started to decline approximately 3000 years before deforestation. Once *Cyathea* was less abundant, it is evident *Pteridium esculentum* briefly increased in this zone, before also declining. Again it was not until after the appearance of exotics that Poaceae and Cyperaceae really became dominant. However, compared with the Travis Swamp, this change in pollen composition was comparatively fast, but significantly slower than at the two Otago sites. Zone 3 charcoal values are lower than Zone 2, although relatively high values were maintained. Cyperaceae suddenly declined soon after the first signs of exotic species.

3.5.3 Glendhu

Prumnopitys taxifolia, Halocarpus and *Phyllocladus* dominated the taxa throughout Zone 1a in the Glendhu core. There are two dips in these species' dominance which correlate with increases in abundances of *Coprosma, Myrsine,* Poaceae, *Centrolepidaceae,* monolete fern spores and charcoal abundance. Zone 1b saw *Prumnopitys taxifolia, Halocarpus,* and *Phyllocladus* begin to decline, despite relatively low levels of charcoal being present. *Pteridium esculentum* occurred, coincident with the obvious increases in fire regime for the first time in this zone, but this occurrence was short-lived. Zone 1c saw a gradual increase in *Nothofagus menziesii* from its low and fluctuating abundance in earlier zones. This gradual increase matched the continued decline of *Prumnopitys taxifolia, Halocarpus* and *Phyllocladus*. Charcoal levels were higher than in the previous zone, although they still remained relatively low. *Pteridium esculentum* occurred again, although only briefly before disappearing and reappearing towards the end of the core. *Coprosma, Myrsine, Poaceae,* and *Centrolepidaceae* increased right at the end of this zone at approximately the same time as *Nothofagus menziesii* briefly declined while still remaining dominant. Zone 2 saw the sudden decline in *Nothofagus menziesii,* while other *Nothofagus* remained dominant for a brief period, before also declining. This decline of all tree and shrub species (apart from *Gaultheria)*, correlated with sudden increases in charcoal abundance of a magnitude greater than those previously experienced. The decline in woody taxa resulted in a corresponding increase in Poaceae, *Empodisma* and *Pteridium esculentum.* Although *P. esculentum* increased initially, it began to decline part-way through this zone, but its decline correlated with a decline in charcoal. Exotic species appeared for the first time at the beginning of Zone 3 and slowly increased. Charcoal values declined further to levels comparable with Zones 1a-1c. Poaceae remained dominant, while *Empodisma* and *P. esculentum* declined further. Trees and shrubs were virtually absent from this zone and only trace levels remained.

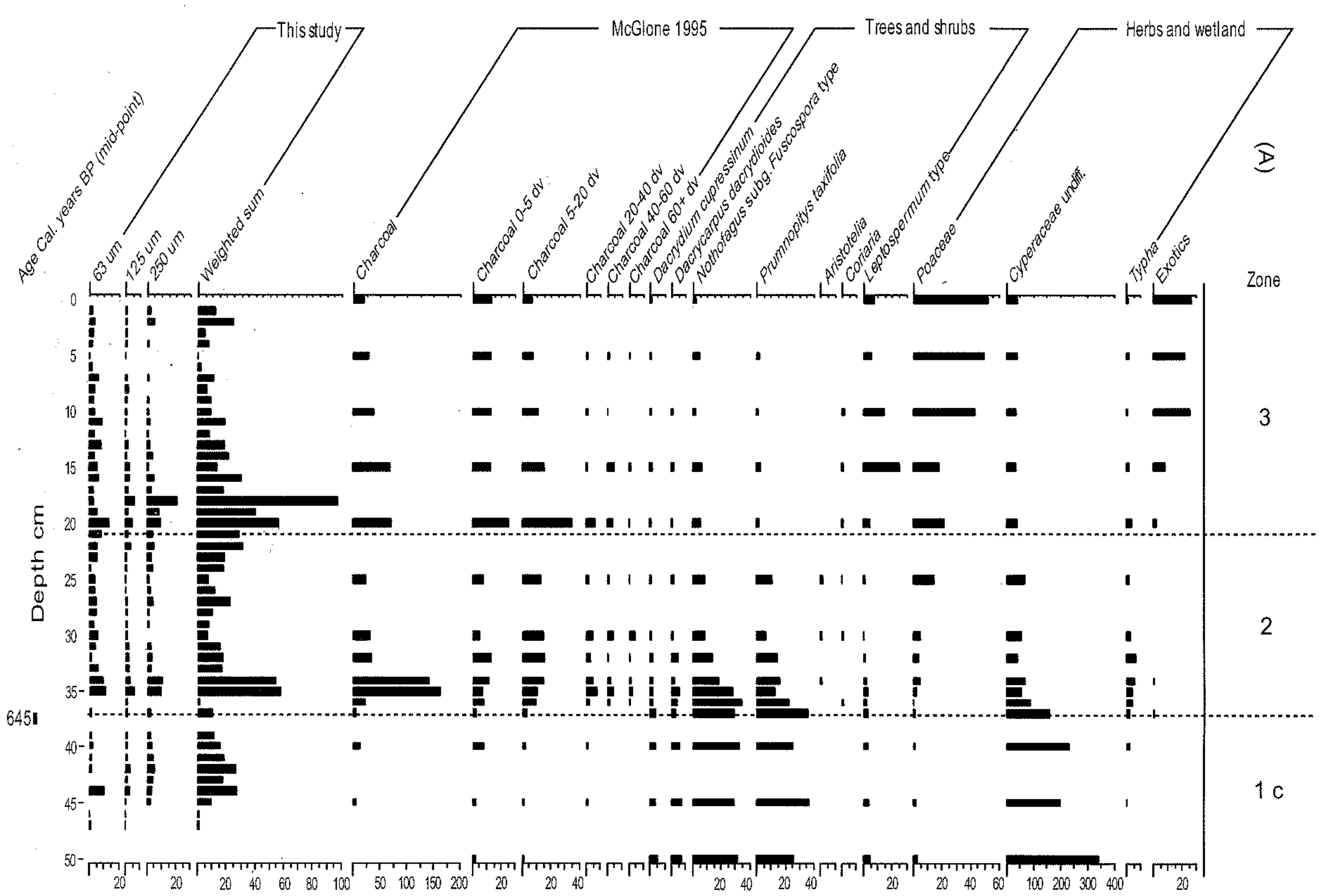
3.5.4. Pomahaka

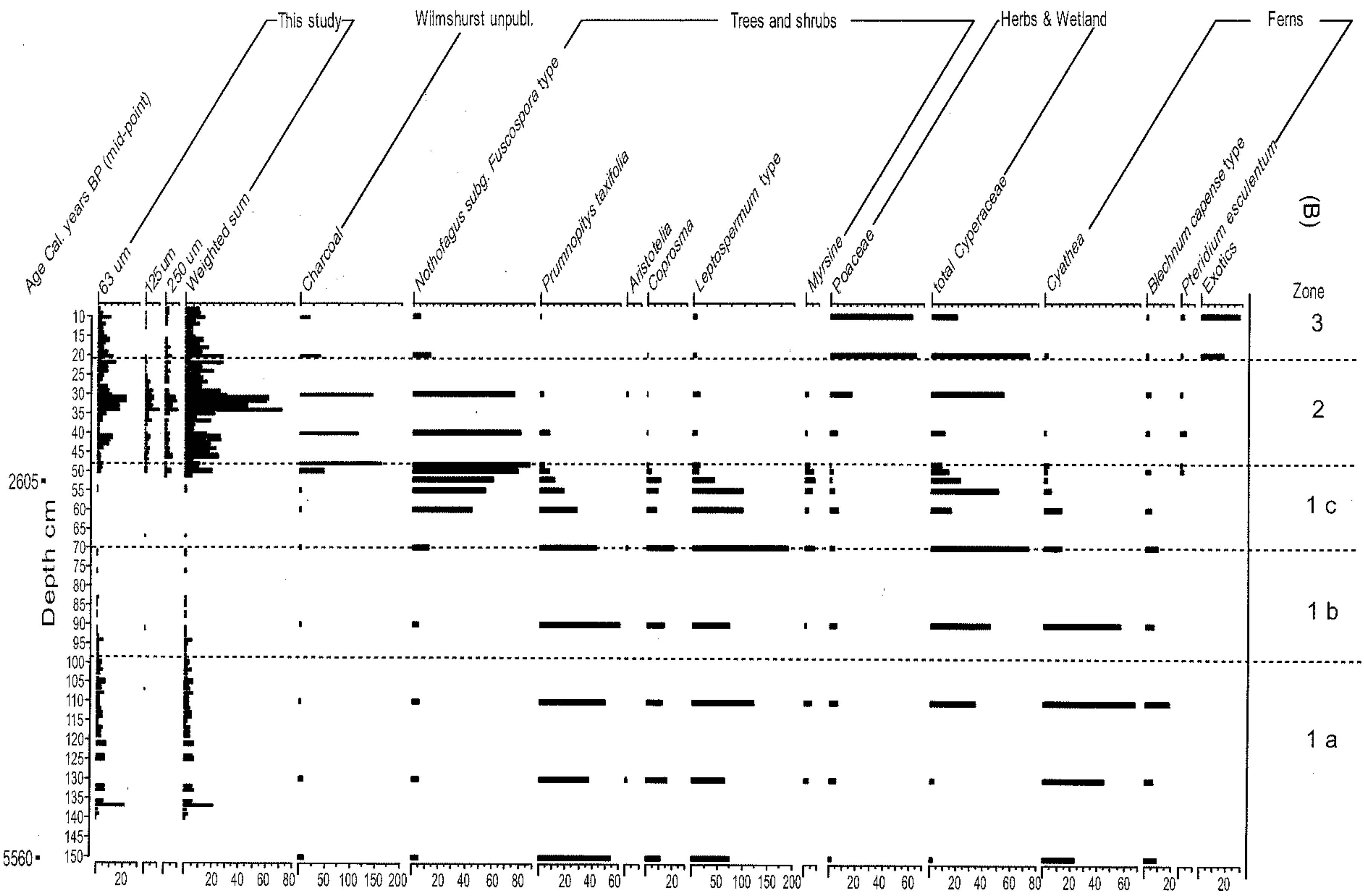
Unfortunately the pollen record for the Pomahaka core is incomplete. Based on the limited data available, it appears that the species composition fluctuated in a way similar to that found at the Glendhu site. Zone 1c saw *Nothofagus menziesii,* *Prumnopitys taxifolia, Halocarpus* and *Phyllocladus* dominate, with relatively low levels of *Coprosma,* Poaceae, Cyperaceae and *Nothofagus* subg. *Fuscospora.* Charcoal levels were relatively low throughout this period. Zone 2 saw an abrupt increase in charcoal which resulted in corresponding changes to the taxa. *Nothofagus* subg. *Fuscospora* and *Gaultheria* briefly increased before declining, while *Nothofagus menziesii, Prumnopitys taxifolia, Halocarpus, Phyllocladus* and all other woody vegetation declined. This decline in woody taxa saw Poaceae, *Empodisma,* monolete fern spores and *Pteridium esculentum* increase in abundance. *Centrolepidaceae* was displaced relatively early in this zone. *Poaceae,* along with *Empodisma* and *P. esculentum* continued to dominate into Zone 3. They were joined by exotics. Woody taxa were virtually absent and showed no signs of increase, despite relatively low charcoal levels towards the end of this zone.

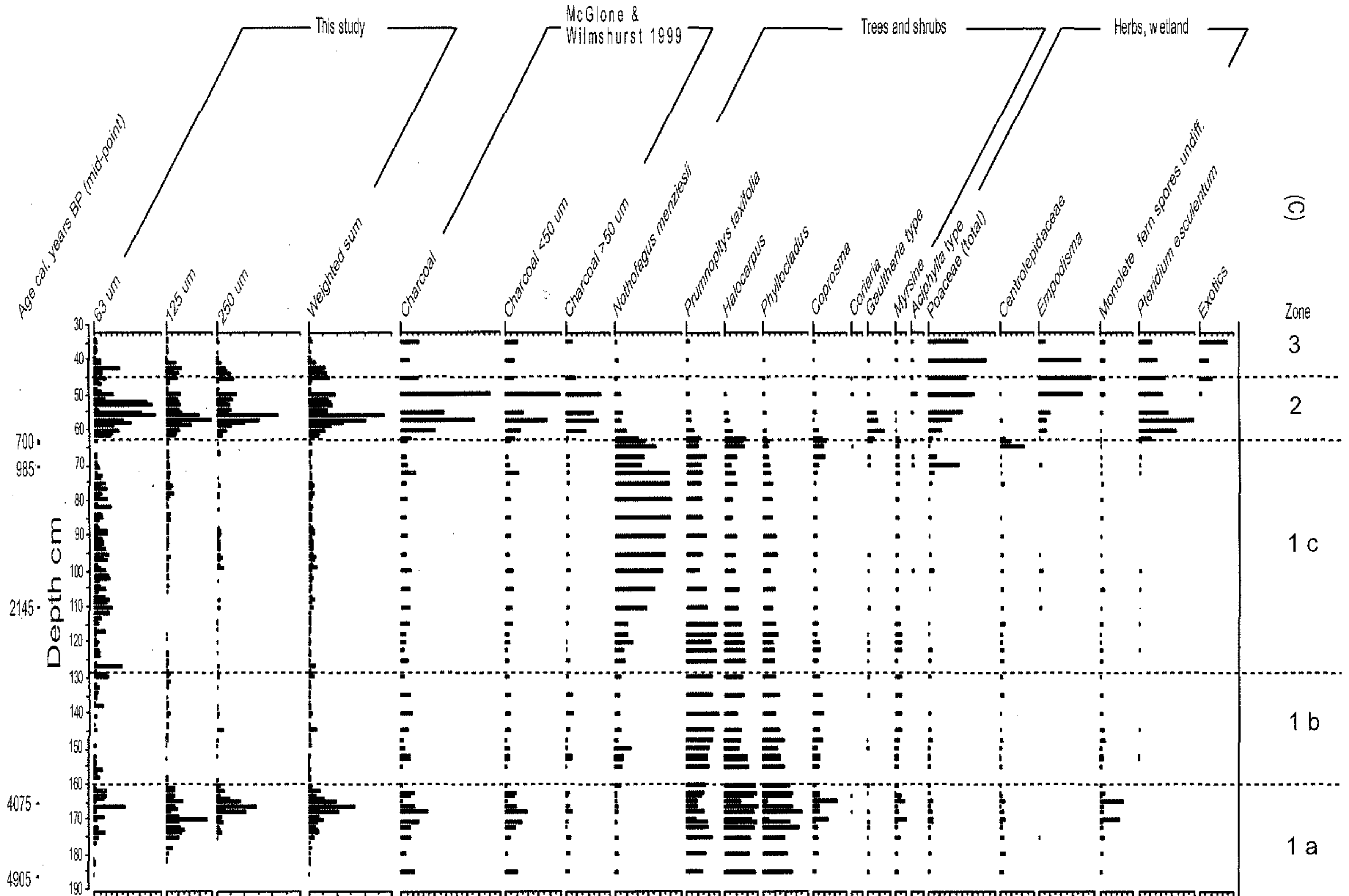
One important feature that can be detected in a comparison of the four pollen profiles is that they change rapidly at the Otago sites at the start of Zone 2, while the changes in the Canterbury pollen profiles are more gradual, especially at the Travis Swamp site.

These general patterns are summarised by Figure 3.5 which shows a drastic decline in woody vegetation at approximately 700 years b.p. and a corresponding increase in herbs and ferns especially *Pteridium esculentum.* Exotic species did not start to occur until European arrival, but soon became a dominant component of the landscape.

Figure 3.5. Charcoal and pollen profiles: (A) Travis Swamp, (B) Halls Bush, (C) Glendhu and (D) Pomahaka


This study
McGlone 1995
Trees and shrubs
Herbs and wetland
(A)
Age Cal. years BP (mid-point)
63 um
125 um
250 um
Weighted sum
Charcoal
Charcoal 0-5 dv
Charcoal 5-20 dv
Charcoal 20-40 dv
Charcoal 40-60 dv
Charcoal 60+ dv
Dacrydium cupressinum
Dacrycarpus dacrydioides
Nothofagus subg. Fuscospora type
Prumnopitys taxifolia
Aristotelia
Coriaria
Leptospermum type
Poaceae
Cyperaceae undiff.
Typha
Exotics
Zone
3
2
1 c
Depth cm
645


This study
Wilmshurst unpubl.
Trees and shrubs
Herbs & Wetland
Ferns
(B)
Age Cal. years BP (mid-point)
63 um
125um
250 um
Weighted sum
Charcoal
Nothofagus subg. Fuscospora type
Prumnopitys taxifolia
Aristotelia
Coprosma
Leptospermum type
Myrsine
Poaceae
total Cyperaceae
Cyathea
Blechnum capense type
Pteridium esculentum
Exotics
Zone
3
2
1 c
1 b
1 a
Depth cm
2605
5560


This study
McGlone & Wilmshurst 1999
Trees and shrubs
Herbs, wetland
Age cal. years BP (mid-point)
63 um
125 um
250 um
Weighted sum
Charcoal
Charcoal <50 um
Charcoal >50 um
Nothofagus menziesii
Prumnopitys taxifolia
Halocarpus
Phyllocladus
Coprosma
Coriaria
Gaultheria type
Myrsine
Aciphylla type
Poaceae (total)
Centrolepidaceae
Empodisma
Monolete fern spores undiff.
Pteridium esculentum
Exotics
(C)
Zone
3
2
1 c
1 b
1 a
Depth cm
700
985
2145
4075
4905

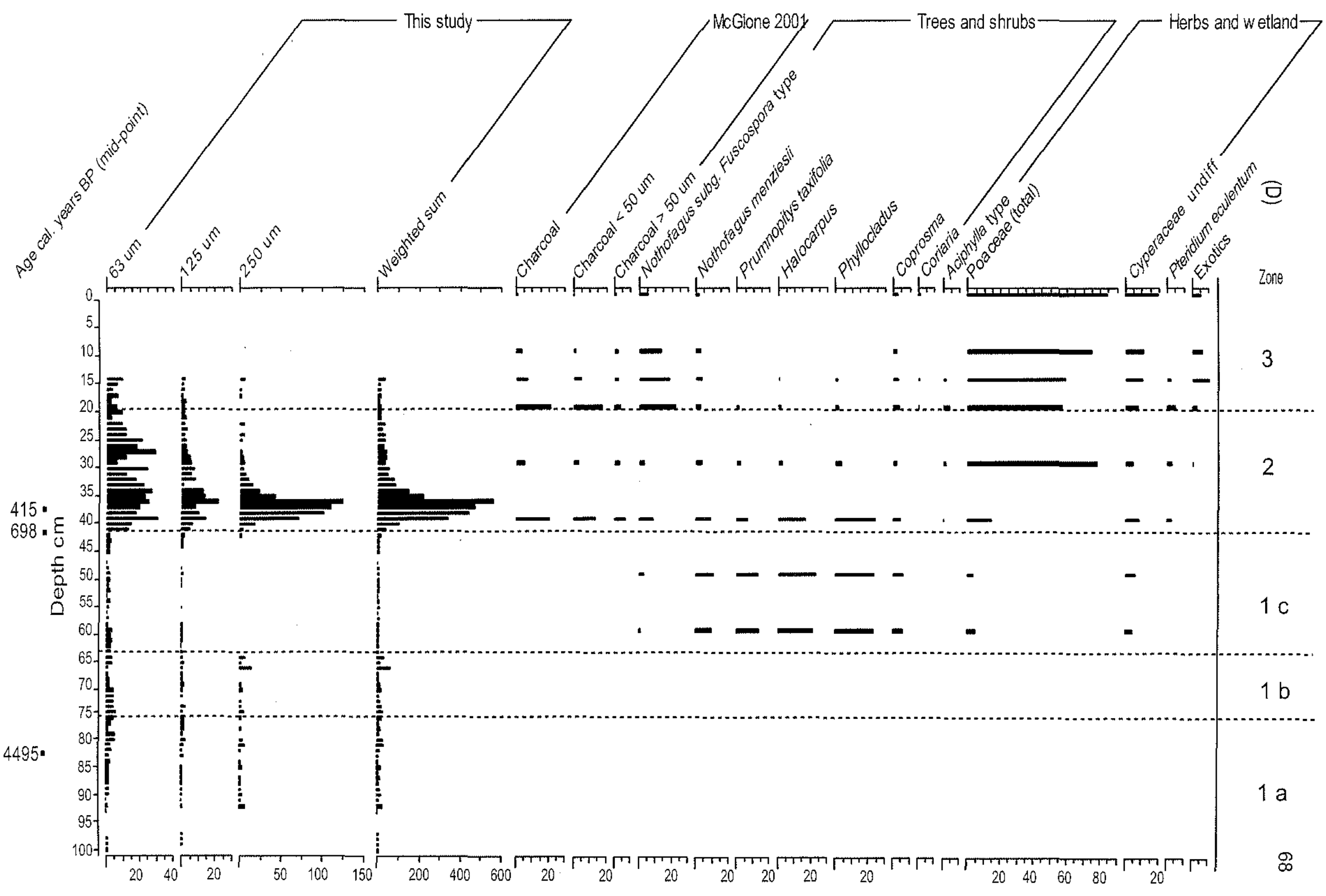
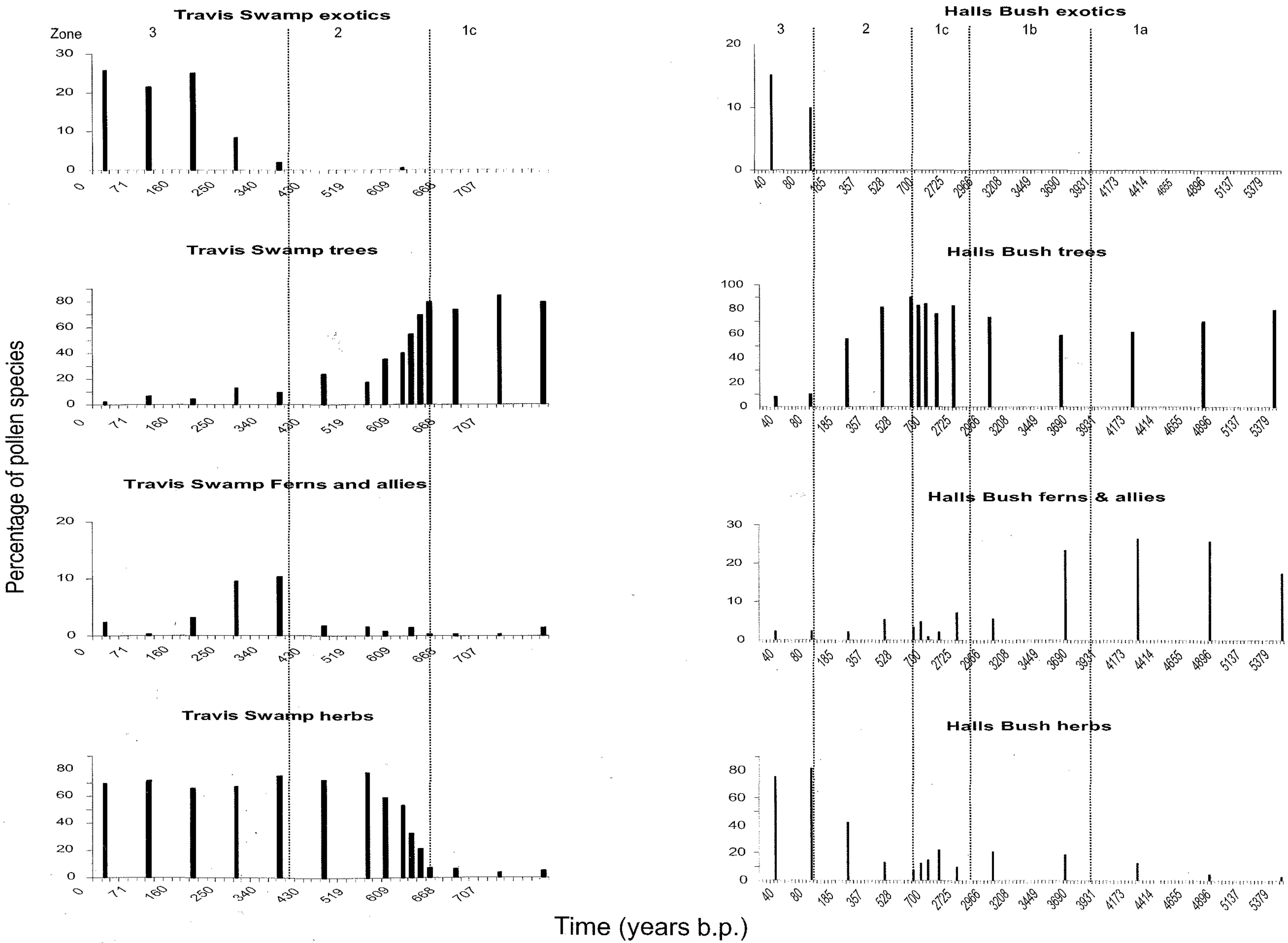
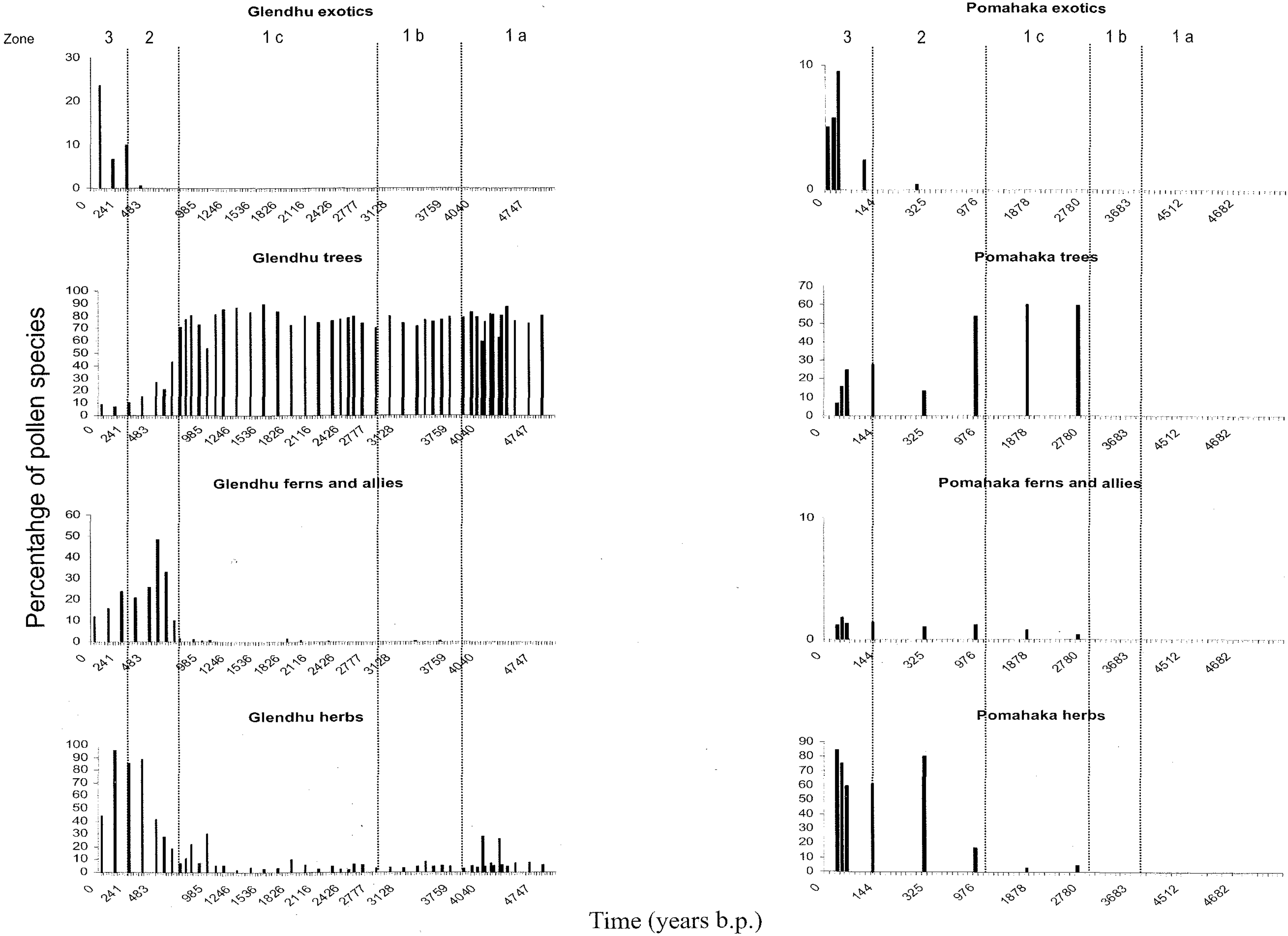

This study
McGlone 2001
Trees and shrubs
Herbs and wetland
Age cal. years BP (mid-point)
63 um
125 um
250 um
Weighted sum
Charcoal
Charcoal < 50 um
Charcoal > 50 um
Nothofagus subg. Fuscospora type
Nothofagus menziesii
Prumnopitys taxifolia
Halocarpus
Phyllocladus
Coprosma
Coriaria
Aciphylla type
Poaceae (total)
Cyperaceae undiff.
Pteridium esculentum
Exotics
(D)
Zone
3
2
1 c
1 b
1 a
Depth cm
415
698
4495

Figure 3.6. Changes in pollen composition



Travis Swamp exotics
Zone
3
2
1c
Travis Swamp trees
Travis Swamp Ferns and allies
Travis Swamp herbs
Halls Bush exotics
3
2
1c
1b
1a
Halls Bush trees
Halls Bush ferns & allies
Halls Bush herbs
Percentage of pollen species
Time (years b.p.)
0
71
160
250
340
430
519
609
668
707
40
80
185
357
528
700
2725
2966
3208
3449
3690
3931
4173
4414
4655
4896
5137
5379



Glendhu exotics
Zone
3
2
1 c
1 b
1 a
Glendhu trees
Glendhu ferns and allies
Glendhu herbs
Pomahaka exotics
Pomahaka trees
Pomahaka ferns and allies
Pomahaka herbs
Percentahge of pollen species
Time (years b.p.)
0
241
483
985
1246
1536
1826
2116
2426
2777
3128
3759
4040
4747
144
325
976
1878
2780
3683
4512
4682

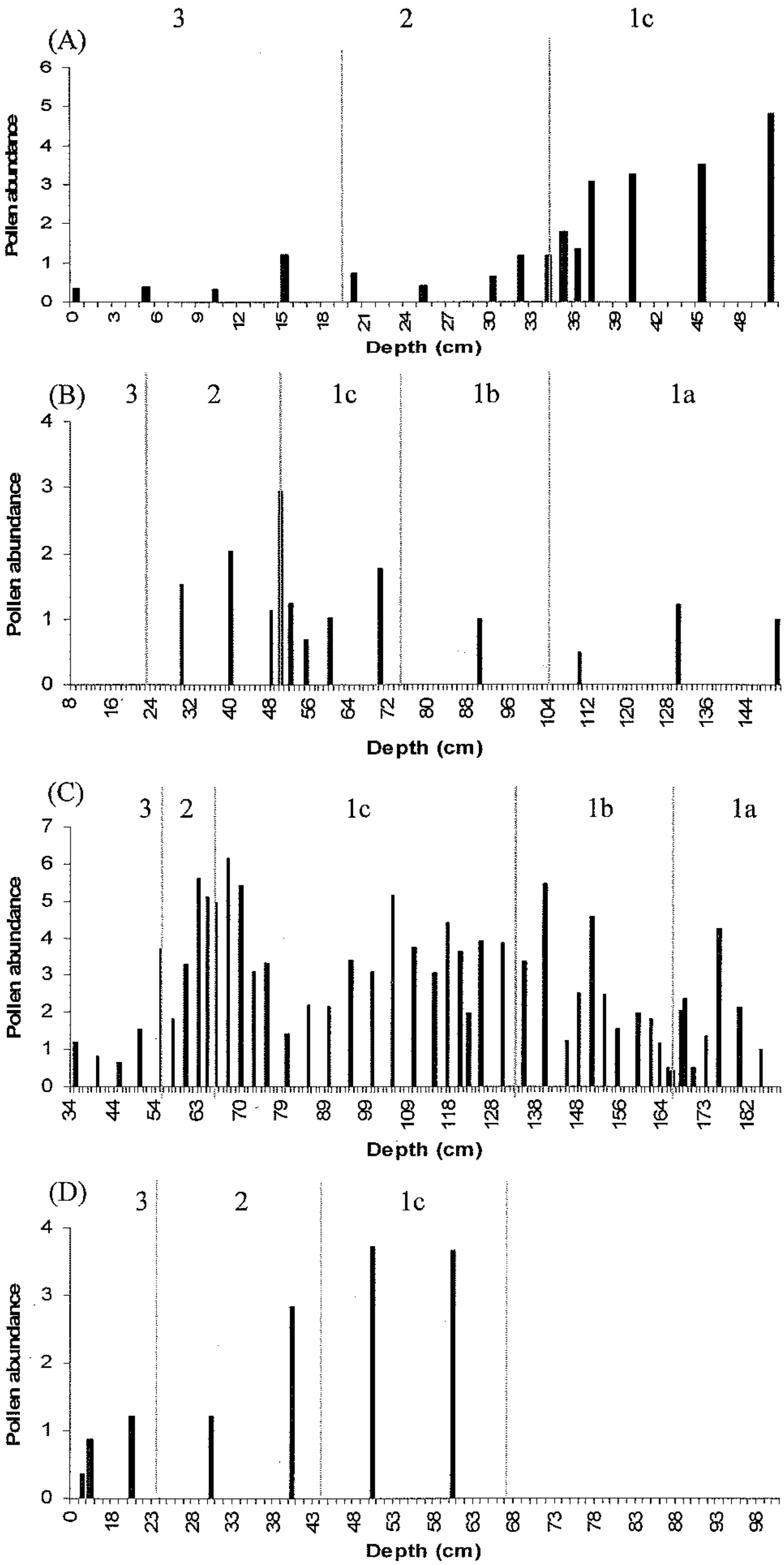


Figure 3.7 Changes in *Dacrydium cupressinum* pollen abundance over time: throughout the different zones (A) Travis swamp, (B) Halls Bush, (C) Glendhu, (D) Pomahaka.

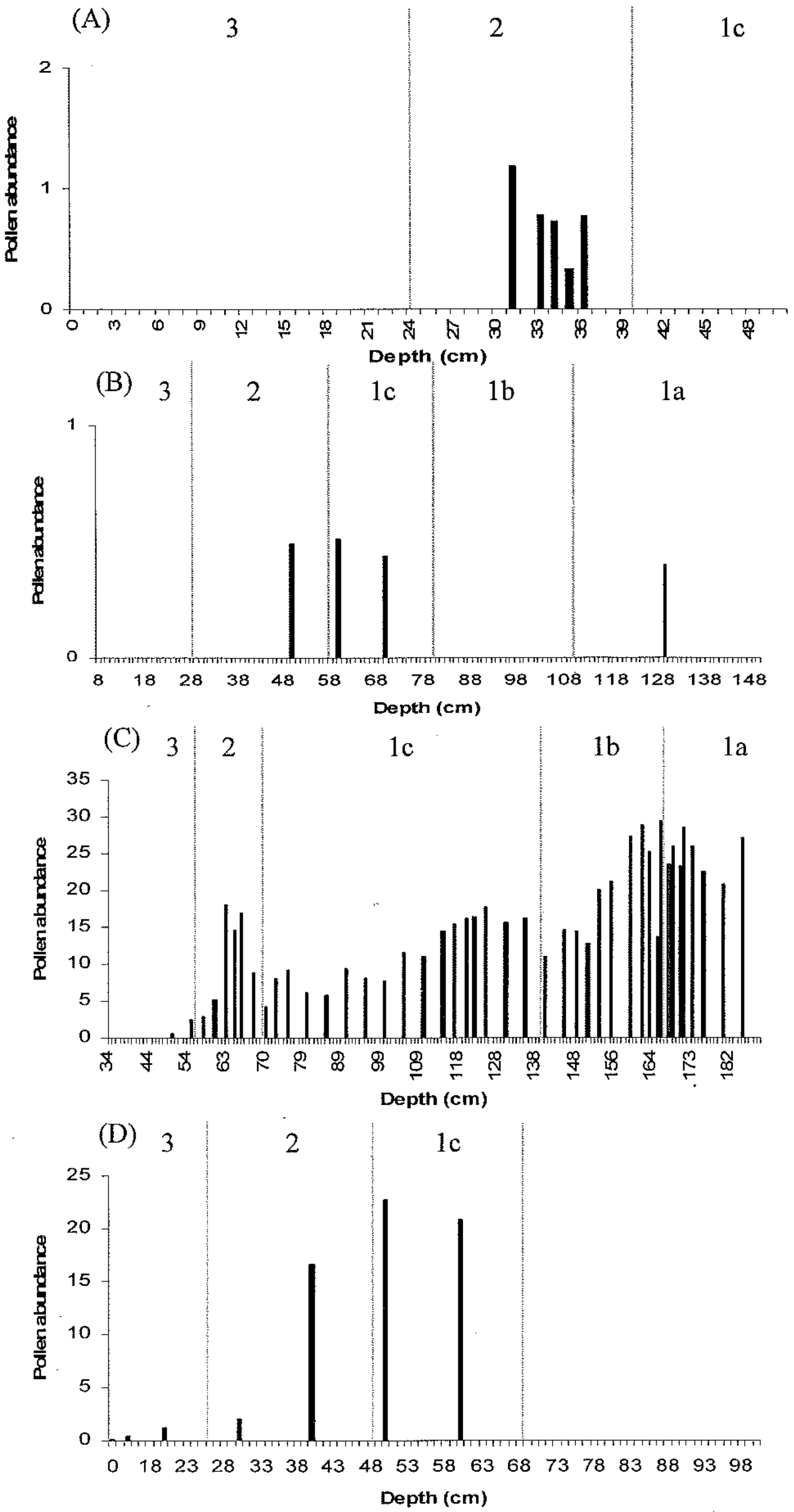


Figure 3.8 Changes in *Halocarpus* pollen abundance over time: throughout the different zones (A) Travis swamp, (B) Halls Bush, (C) Glendhu, (D) Pomahaka.

Note the changes in dominance between *Dacrydium cupressinum* (Fig 3.7) and *Halocarpus* (Fig 3.8) between different zones fluctuate up and down. Note the high values of *Halocarpus* in Zone 1a in both the Halls Bush core and Glendhu, and the subsequent decline at the Start of Zone 1b. This decline was correlated with associated increases in *Dacrydium cupressinum. Halocarpus* continued to fluctuate, but in general declined until the end of Zone 1c.

Profiles of charcoal collected through sieving during the present study are similar to those collected through counting on pollen slides (Fig 3.9). However the extent of any correlation depends on size class. Correlations are best between similar size classes. Thus it was no surprise that correlations between the sieved 63-125 μm size class and 0-5 μm on the pollen slides are poor, due to the difference in location of fire i.e. source area and subsequent mechanisms / modes of atmospheric transport that the two size classes represent. From the sieved-sample counts in this study, there are some correlations with pollen-slide sizes classes, 5-20 μm and greater, with the maximum correlation for the 20-40 μm pollen-slide size class. Thus 63-125 μm from sieving methodology and 20-40 μm from pollen-slide counts are representative of the same area.

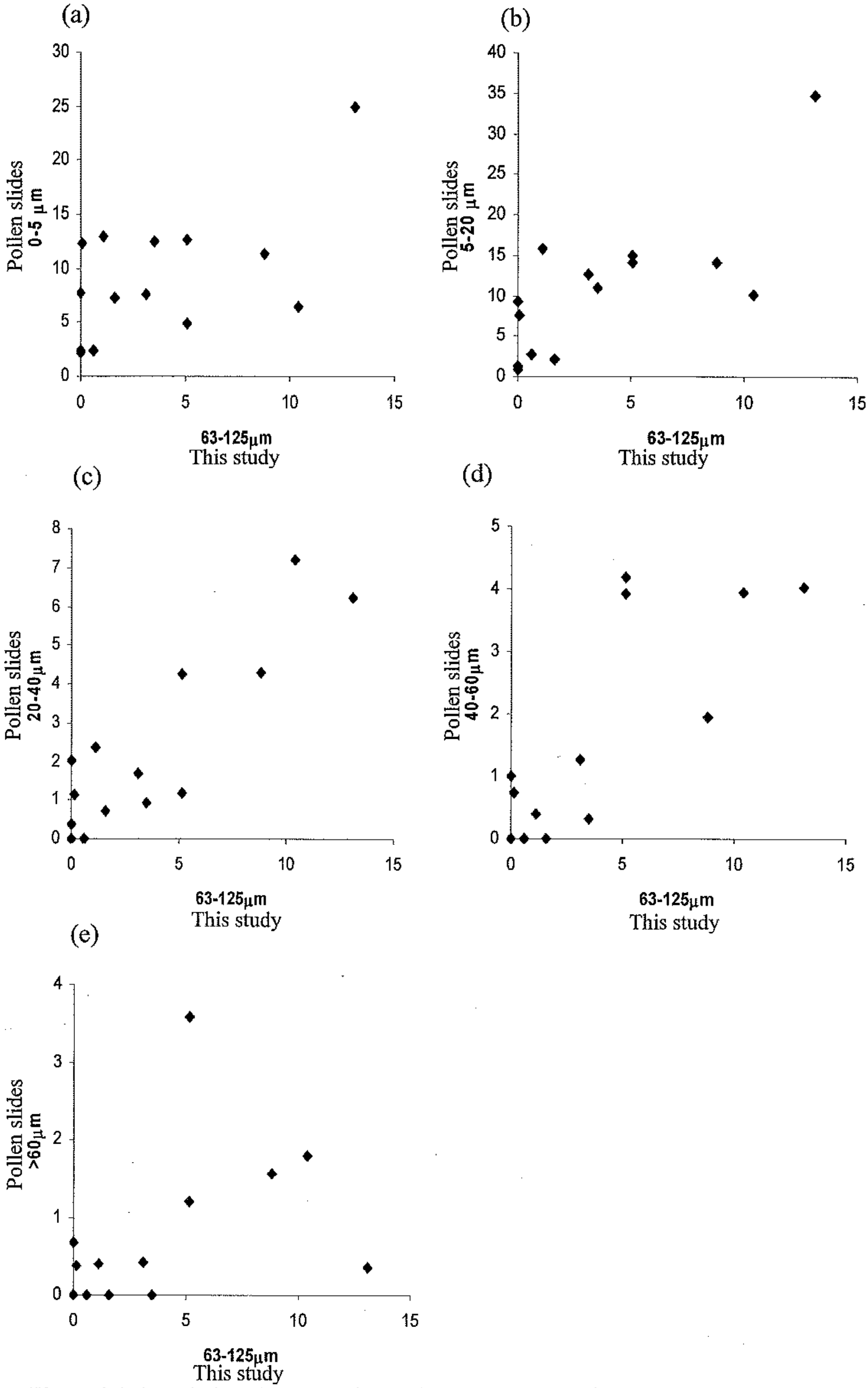


Figure 3.9 Correlations between charcoal counts from previous pollen-slide analysis and from this study using a stacked sieve method. (a) pollen-slide 0-5µm vs this study 63-125 µm (b) pollen-slide 5-20 µm vs this study 63-125 µm (c) pollen-slide 20-40 µm vs 63-125 µm (d) pollen-slide 40-60 µm vs this study 63-125 µm (e) pollen-slide 60+ vs this study 63-125 µm

Chapter Four

Discussion

The aim was to test for: any relationship between New Zealand South Island climate and fire regimes; a sudden change in charcoal abundance centred on Māori and European arrival; any geographical trends related to the start of deforestation; and variations between coastal and inland sites. Another endeavour was to determine the most suitable charcoal size for future work to concentrate on, and to develop and refine new methodology, developed overseas, so that it was suitable for use in New Zealand. In the following sections, each aim will be discussed in detail.

Due to the extended periods of time invested in refining the methodology, only four cores were analysed. This low level of replication is compounded by the different rates of peat growth between and within cores, thus making statistical comparisons difficult. However, changes in charcoal input are clear and unmistakable. These differences, coupled with the associated pollen data, allow useful interpretations to be made about the effects that climate change, colonisation, and the intrinsic flammability of some species have on local and regional fire regimes.

4.1 Methodology critique

Potassium hydroxide was successfully used to help disintegrate and bleach organic vegetation. This increased the contrast between non-charcoal and charcoal particles, making identification easy. The analysis of 63-125 μm and 125-250 μm classes, which had previously not been attempted before with this methodology, was successfully achieved through Increasing the magnification of the individual photos, allowing increased magnification and thus resolution. These adjustments were highly successful and resulted in strong correlations occurring between manual and computer counts. Data collected in previous studies on the same cores during pollen analysis also followed this general pattern when the corresponding size classes were compared.

The use of digital photography and image analysis software is a valuable and accurate tool to analyse charcoal abundance. Although this methodology has resulted in extremely promising results, and has great potential, in hindsight there could be some fundamental improvements that would greatly aid in the accuracy, speed of analysis and understanding of results.

Accuracy and speed of analysis would be aided if experiments were designed to work out the exact amount of KOH that can be added before detrimental effects begin to occur. If additional vegetation can be removed from the samples without causing damage to the charcoal particles this would greatly improve the accuracy of the study and speed of analysis.

Improvements in photography could also be achieved, to improve the contrast between charcoal and vegetative matter, reducing the need for manual checking, which would drastically increase the speed of analysis, be this via additional chemicals that freely bind to charcoal or the use of fluorescent lights.

It would have been beneficial to conduct these experiments, but unfortunately time restraints precluded this.

Due to these time restraints, experiments were not undertaken to detect the level of fragmentation through this methodology. However, correlations between charcoal data derived from pollen counts resulted in the best correlations occurring between, 63-125µm from this study and the 20-40 µm size class from the pollen data. This close resemblance between these two size classes indicates that both size classes were of similar dimensions before they were put through different sampling procedures, thus significantly less fragmentation occurred than in pollen preparation.

4.1.2. Importance of Size

A comparison between the 0-5 and 5-20 μm particles counted on pollen slides, with the 63-125μm size class, resulted in poor correlations, therefore clearly come from more distant sources or resulting from fragmentation of larger particles. The three different size classes employed in this study are likely to have come from different source distances, as a result of different theoretical atmospheric height and settling velocity of each individual size class (Patterson *et al.* 1987, Clark 1988c, Clark and Patterson 1994, Clark and Royall 1995, Clark *et al.* 1996, Laird and Campbell 2000, Ohlson and Tryterud 2000). This is clearly shown through the lack of correlation between the three different size classes, and the instances in which only the small size class was detected. This difference in source area that the three different size classes represent, is most noticeable in pre-deforestation times, suggesting the majority of the charcoal is derived from distant sources, or fine, highly combusted fuels. The lack of sudden change occurring in the pollen profiles pre-settlement further supports the dominance of regional input. i.e. possible small fires occurring relatively often throughout the large regional zone represented by the small particles.

When fires occur close to the bog however, such as the case at Zone 1a in the Glendhu core, correlation can be strong between all three size classes. This high correlation occurs between the different particles even when region fires are occurring, because the regional input is so small compared with the local input that it is insignificant. The increased level of correlation found in Zone 2 and 3 compared with the previous Zones suggests fires were occurring locally: This is supported by the greatest representation of large particles coinciding with the highest levels of small particles in these Zones (Novakov *et al.* 1994). Thus the higher the proximity of the fire the stronger the correlation becomes.

Although it is clear that the combination of all three size classes resulted in a more complete picture evolving, when time, accuracy and the relatively high level of correlation is considered it would be more beneficial to use only the 250 μm charcoal class. This particle range was significantly faster to process than the other two size classes, about one day compared to about three week to do the other two size classes, through correlations between manual and computer counts it was clear that computer-assisted counts for this size class are the most accurate. Although this size class cannot detect distant regional fire activity on its own, the speed of analysis means a large number of replicate sites across a region could be sampled in the time that it would take to sample all three size classes of a single core. Thus it would be possible for a more accurate regional picture to be created. More information could be obtained through solely concentrating on this size class. As the original origin of the particles can be more accurately predicted due to the reduced area that it could possibly have been derived from, Thus increasing the resolution of the study, making it easier to make connections with climate fluctuations and changes in fuel

4.2 Climate

This study and others (Burrows 1960, Molloy *et al.* 1963, Molloy and Cox 1972, McGlone and Topping 1973, Goh *et al.* 1977, Molloy 1977, Burrows 1983, Davidson 1984, McGlone 1989, Burrows and Russel 1990, Ogden *et al.* 1998) clearly show that natural (pre-settlement) fires occurred throughout the eastern half of the South Island, and in some regions played an integral part in the landscape before human arrival (McGlone and Moar 1998, McGlone and Wilmshurst 1999b). The discovery of charcoal older than the upper limits of valid charcoal dating (40,900yr b.p.) by Harvey (1974) and (Goh *et al.* 1977) reflect the antiquity of burning. However the occurrence of natural fires on the South Island was relatively infrequent. Ogden *et al.* (1998) concluded from a variety of documented fire histories that the average return time of fire was approximately 2000 years, hence the lack of fire adaptations that are present in the New Zealand flora (Burrows 1990, Ogden *et al.* 1998). The significantly higher charcoal values throughout Otago sites, Pomahaka and Glendhu, compared to the two Canterbury sites, Travis Swamp and Halls Bush, reflect differences in natural fire regimes due to climatic differences, which affect ignition sources and fuel.

Since the fire frequency and, consequently, charcoal production are so closely linked to weather and long term climate, it is no surprise that peaks in charcoal production closely follow such phenomena. It is difficult to differentiate whether this is due to increased size of fire, intensity, type or simply increased number. Regardless of the cause of the changes in charcoal production, it does appear that shifts in climate, both long-term and short-term, are responsible for changes in fire regimes both before and after colonisation, through changes in humidity, wind, temperature, precipitation, change in vegetation or lightning activity.

4.2.1 Regional difference

In all four cores, charcoal abundances fluctuated over time. These differences in charcoal abundance are consistent with contemporary climatic differences that were expressed in the past.

Notably more charcoal was detected in the Otago cores than the Canterbury cores signifying a higher frequency of fires. The increased number of randomly occurring fires, throughout the region, increases the probability of a fire occurring in close proximity to the bog. As a result more large and small charcoal particles were detected in the Otago region. The low frequency of fires occurring in the Canterbury region resulted in only small charcoal particles, 63-125 μm, being detected because the low numbers of fires that did occur were not in close proximity and thus large particles, >125 μm were excluded.

Higher incidences of lightning in Otago than in Canterbury (McGlone 1989, Rogers and McGlone 1989, Burrows 1996), combined with the more continental climate leading to significantly higher water deficits, result in fires being comparatively more frequent and larger than those found in the Canterbury region.

The absence of large charcoal particles >125μm in both of the cores from the Canterbury region, Halls Bush and Travis Swamp, indicates that natural fires did not occur locally during this period. The presence of small charcoal particles, 63-125 μm, signifies that natural fires did occur. Although it is clear that fires occurred, the proximity of such events is unknown. However the fact that the pollen diagram did not show increases in fire susceptible plant communities suggests that wherever this charcoal derived from, it is a distant source. It is even plausible that these particles could have derived from Australia (Wilmshurst 2004). Apart from this period at the ends of Zone 1a at Halls Bush there was no sign of fire activity throughout the three pre-deforestation zones in either of the Canterbury sites.

The South Island experiences low levels of lightning activity compared to the rest of the world (Tomlinson 1976). (With 2-10 thunder days per annum occurring on the east coast: 50-60 % occurring in the summer) (McGlone 2001). Unlike in Australia, where lightning strikes occur in absence of rain (Holdaway 2004) and hence are responsible for a large number of fires, heavy rain accompanies lightning activity in the South Island (Tomlinson 1976), resulting in very low levels of actual strikes causing fires as any ignition is likely to be put out even before it gets established (Ogden *et al.* 1998).Thus before human arrival, the chances of a fire occurring were relatively low since a thunderstorm had to co-occur with an adequately dry period. Despite this inefficiency of lightning due to the associated weather phenomena, it is still thought to have been the main ignition source in the South Island prior to human arrival (Molloy 1977, McGlone 2001). The presence of charcoal in varying amounts before major deforestation occurred clearly shows some of these strikes must have eventuated in fire, especially in the Otago region. The relative frequency of these fires varied drastically within cores due to changes in climate between the different zones.

The fact that local and region fire regimes were limited by a suitable ignition source is reflected in the sudden increase in fire activity after Polynesian arrival (Cofer *et al.* 1994, Baker 1995, Vazquez and Moreno 1998, Mensing *et al.* 1999, Tinner *et al.* 1999, Li 2000, Tinner *et al.* 2000, Cardille and Ventura 2001, McCarthy *et al.* 2001, McGlone 2001, Tilman and Lehman 2001, Caldararo 2002, Parshall and Foster 2002, Vazquez *et al.* 2002, Laterra *et al.* 2003). Thus fires were limited by ignition before settlement.

The fact that even after human arrival Otago sites consistently had more charcoal suggests that lightning was not the only limiting factor, with fuel moisture being a vital determinant in determining the local and regional fire regime, even when there are effective ignition sources present (humans). Thus moisture content constrained fire frequency, before and after human settlement (Zackrisson 1977, Johnson 1979, Cwynar 1987, Clark 1989, Johnson and Gutsell 1994, Bessie and Johnson 1995, Long *et al.* 1998, Niklasson 1998, Veblen *et al.* 1999, Carcaillet *et al.* 2001, Heyerdahl *et al.* 2001, Kafka *et al.* 2001, Brown and Hebda 2002, Parshall and Foster 2002, Vazquez *et al.* 2002, Gavin *et al.* 2003, Westerling *et al.* 2003).

4. 2.2 Comparisons between coastal and inland sites

There was a difference in pre-settlement charcoal profiles (and thus fire regimes) between coastal and inland sites. There was a tendency for higher levels of charcoal to occur at the coastal sites compared with their counterpart inland sites. This difference is more obvious within the smaller particle sizes, 63-125 μm and 125-250 μm, with very little difference between the >250 μm particles between the two sites. Thus, these findings at the coastal sites reflection of the dominant westerly wind patterns (Burrows and Greenland 1979, McGlone and Bathgate 1983, Neal 1993), resulting in higher amounts of charcoal being carried to these sites. This difference is not as obvious in the Canterbury sites reflecting the lower general fire frequency in this area.

4.2.3 Temporal variation

At both Glendhu and Halls Bush, a sudden increase in fire activity occurring approximately 5000 years ago was detected, These findings correspond with major climatic change resulting in the climate becoming cooler and drier in this period (McGlone and Topping 1977). This change resulted in major glacial reduction in most valleys throughout the Southern Alps (Gellatly *et al.* 1988) and corresponding increases in *Halocarpus* and low levels of *Dacrydium cupressinum.* Thus the sudden influx of charcoal occurring at this time is a result of drier conditions throughout the East Coast due to decreased precipitation. This period was relatively brief, before fire frequency declined again in Zone 1b, which was reflected by a reduction in charcoal abundance even within the smaller size class, indicating that the decrease in fire frequency was regional. This change was the result of increased precipitation and decreased temperatures. These changes are reflected in changes in pollen profiles throughout all four cores, showing that *Dacrydium cupressinum* began to increase and that a corresponding decrease in *Halocarpus* occurred shortly after the end of Zone 1a. Since *Dacrydium cupressinum* is rarely common where the annual precipitation is under 1200 mm (Franklin 1968), low levels of charcoal found throughout zone 1b in all cores was probably a direct result of a wetter, cooler climate (McGlone and

Bathgate 1983, McGlone *et al.* 1995), resulting in fuel having higher moisture levels and hence being less flammable due to increased precipitation and decreased evaporation. Pomahaka's present day climate is drier than other sites (Shearer 1973). If Pomahaka were also relatively drier throughout the Holocene this would explain why charcoal levels did not decline until later on in this period. Charcoal nearly disappeared in Zone 1c, *Dacrydium cupressinum* continued to increase into Zone 1c with *Nothofagus menziesii* and *N. Fuscospora* type becoming increasingly dominant, signifying continued high levels of precipitation (McGlone and Bathgate 1983, McGlone *et al.* 1995). McGlone *et al.* (1995) showed that there was a corresponding increase of aquatic and semi-aquatic taxa, *Myriophyllum* and *Botryococcus,* at the same time as *Nothofagus menziesii* increased. Thus the lack of charcoal throughout Zone 1c is due to high levels of annual precipitation and continued cool conditions.

Although *N. Fuscospora* type was present in the Otago sites, it was in very low values, probably a reflection of the long dispersal capabilities of this species rather than a local population (Myers 1973, McGlone *et al.* 1996). This absence is due to *N. Fuscospora* type's lower susceptibility to high levels of water deficit (Ogden *et al.* 1996), allowing *N. menziesii* to be competitively dominant. Increased precipitation allowed *N. Fuscospora* to spread further south, but the drier, more continental climate of Otago prevented its continued expansion. Even though moisture levels throughout the East Coast had significantly increased in Zone 1c, some areas of Otago were significantly dry enough to allow fires to persist. The occurrence of charcoal in the Glendhu site and minimal levels in the Pomahaka site is a reflection of the dominant westerly winds.

Climate differences between and within sites change due to shifts in dominant wind and ocean currents associated with different weather phenomena such as El-Niño and La-Niña which are well known to affect weather patterns in New Zealand (Tallis 1975, Swetnam and Betancourt 1990, Salinger 1991, Neal 1993, Basher 1996, McKenzie *et al.* 1996, McKerchar and Pearson 1996, Mullan 1996, Nicholls 1996, Salinger 1996, Thompson 1996, Zheng 1996, McGlone and Wilmshurst 1999b, Hess *et al.* 2001, Westerling *et al.* 2003). Although the Southern Oscillation has a strong effect on the New Zealand climate (Gordon 1985), such fluctuations in the weather due to such phenomena are unlikely to be picked up in this study due to the slow growth rate of peat and the relative lack of accurate carbon dates. Long-term changes in climate, however, are instrumental in determining local and regional fire regimes, with these effects clearly being depicted between and within sights, with charcoal abundance being correlated with such patterns.

4.2.4 Peat deposition

Variations in peat deposition further reflect these variations in climate over time and vegetation cover, which affects the amount of water reaching the bog (Latz 1973, Whitlock *et al.* 1994, Mark *et al.* 1995, Enache and Prairie 2000, Bohlin *et al.* 2001, Klarqvist *et al.* 2001a, Nilsson *et al.* 2001, Bragg 2002). Excluding the high values of peat deposition at the top of each core, which is more a reflection of relative compacted instead of actual peat deposition, peat accumulation was generally slow, compared with overseas rates, throughout all four cores, probably as a result of cooler winters and drier summers (Wilmshurst *et al.* 2002). The high rate of peat growth, between 82-138 cm (Zone 1a), at the Pomahaka site may reflect high rates of runoff due to low levels of surface vegetation and ground litter. Peat growth declined at 42-82 cm due to forest expansion at this time as a result of a damper climate. The resultant increase in surface vegetation and ground litter meant that a higher proportion of water was absorbed, reducing the amounts of water reaching the bog. Thus the wetter climate at this time is a result of a cooler climate reducing the evaporative process, not increased precipitation. Forest was established significantly earlier around the Glendhu site (McGlone and Wilmshurst 1999b), due to a higher annual rainfall (Shearer 1973). The higher levels of evaporation throughout Zone 1a resulted in peat growth being initially very slow. Increased peat growth occurred near the end of this Zone, due to increased water reaching the bog as a result of two local fire events occurring close to the bog removing both surface vegetation and ground litter. These fire events were characterised by sudden, but temporary, changes in the pollen composition, with a decline in *Prumnopitys taxifolia, Halocarpus, Phyllocladus* and corresponding increases in *Coprosma, Coriaria, Myrsine, Poaceae, Centrolepidaceae* and *Monolete* fern. These were the only local fire events occurring before complete deforestation in all four sites. Even though vegetation recovered, peat growth remained unchanged from Zone 1a to Zone 1b, due to decreased evaporation. Peat growth increased again going into Zone 1c as a result of increased precipitation

(McGlone and Bathgate 1983, McGlone *et al.* 1995). A low number of actual dates available for the two Canterbury sites made such interpretations difficult. However, high rates of peat growth during Zone 1c (37-113 cm) reflect the pattern found in the two Otago cores, which suggests high levels of precipitation and relatively low levels of evaporation resulting in high moisture content in the bogs making decomposition slow.

During periods in which vegetation was not present, or was destroyed by natural fire, a considerable increase in peat growth resulted, due to reduced levels of water absorption, and thus increased levels of water reaching the bog resulting in decreased decomposition (Ahlgren and Ahlgren 1960, Tolonen and Turunen 1996, Enache and Prairie 2000). The low resolution, because of the lack of dates, occurring after deforestation and the nature of the steep negative exponential curve due to different degrees of compression, it was not possible to conclude that deforestation as a result of Polynesian and European fires significantly increased peat growth. Increased growth should be expected due to increased run off (McGlone and Wilmshurst 1999b), which decreases decomposition which is the main determinant of peat deposition (Meentemeyer 1978, Harmon *et al.* 1986, Kuhry and Vitt 1996, Bohlin *et al.* 2001, Klarqvist *et al.* 2001b, 2001a) Zone (1 b and 1c) resulting in increased growth due to decreased evaporation and increased precipitation especially in the case of Zone 1c.

4.2.5 Fuel constraint

Although Glendhu has a higher annual rainfall (746 mm) than Pomahaka (506 mm) (Shearer 1973), it had higher charcoal levels, caused by increased fuel continuity due to higher levels of productivity. The importance of fuel continuity is clearly shown in the contrast between Glendhu and Pomahaka. Fire activity was precluded after the first major fire event, at Pomahaka, due to lack of fuel continuity, while higher precipitation rates occurring in the Glendhu region allowed a higher rate of fuel increment per year and hence being able to support another large fire (White 1979, Pyne and Goldammer 1994, Bond and van Wilgen 1996, Moore 2000, Pyne 2001, Vazquez *et al.* 2002, Huber and Markgraf 2003). Thus, although drier environments are more prone to catastrophic fires, they take significantly longer to recover from such devastation due to lower rates of productivity. Because of low levels of fuel after such major peaks any other resultant fires were most likely small and constrained, most likely surface fires due to the lack of continuous fuel (Heinselman 1973, White 1979, Romme and Knight 1981, Carcaillet 1998, Hely *et al.* 2000, Higgins *et al.* 2000). This supports other such findings overseas that suggest that the time since the last fire has a significant effect on the behaviour of subsequent fires (Habeck and Mutch 1973, Luke and McArthur 1978, Clark 1988a, 1988b, Whelan 1995, Carcaillet *et al.* 2001).

4.2.6 Climate Conclusion

Changes in charcoal abundance, species composition and peat growth lead to the conclusion that the climate across the East Coast of the South island was considerably drier than that present in Zone 1a, with forest expansion being restricted in the driest areas (Pomahaka). The transition between this zone and Zone 1b did not result in major changes in annual precipitation but increases were likely. The major change resulted from decreased temperatures creating a more humid climate with low levels of evaporation occurring. This increase in soil moisture allowed the acceleration of forest expansion to occur. Zone 1c saw increased precipitation and continued low temperatures

Changes in long-term climate conditions were instrumental in determining the frequency of natural fires through their influence on vegetation composition. The absence of significant levels of charcoal in Zone 1c is partly due to the relative flammability of the dominant vegetation type which is predetermined by climatic conditions at that time as previously demonstrated. Zone 1c throughout all cores is marked by the rise to dominance by *Nothofagus sp* which displaced the *Prumnopitys taxifolia, Halocarpus,* and *Phyllocladus* which previously dominated. Thus the disappearance of fire from the equation is a result of high mineral content found in the wood and leaves of *Nothofagus* retarding any fire (Vines 1981). This would be aided by microclimatic changes (Casagrandi and Rinaldi 1999, Cardille and Ventura 2001) resulting in available fuel being sheltered from the evaporation process, meaning that more extreme droughts would be necessary to make available fuel sufficiently flammable to carry a fire.

4.3 Human impact

After human arrival, disturbance becomes the most dominant determinant of species composition and thus pollen species can no longer be used to predict climatic changes over time.

4.3.1 Temporal variation

In all four cores, Polynesian arrival was signified by a distinct increase in charcoal, indicating that fire frequency and/or intensity had increased dramatically. This pattern is consistent with other observations of Polynesian movements across the Pacific (Kirch 1996) and previous studies in New Zealand (McGlone 1978, 1983, McGlone and Bathgate 1983, Davidson 1984, Bussel 1988, Caughley 1988, McGlone 1989, Anderson and McGovern-Wilson 1990, McGlone *et al.* 1994, McGlone and Basher 1995, Kirch 1996, McGlone and Wilmshurst 1999a, Hall and McGlone 2001, McGlone 2001, Byrami *et al.* 2002, Caldararo 2002) and of the impact of first human settlement elsewhere around the world (Heinselman 1973, Edney *et al.* 1990, Mottzkin *et al.* 1993, Bradshaw *et al.* 1994, Kershaw *et al.* 1994, Hoffmann 1996, Umbranhowar 1996, McGlone and Moar 1998, Moore 2000, Tinner *et al.* 2000, Turney *et al.* 2001, Pitkanen *et al.* 2002, Szeicz *et al.* 2003). This Polynesian increase in fire is especially evident in the two Canterbury sites, where there was a substantial period of no charcoal input prior to settlement, compared to the Otago sites where there was charcoal input on a relatively regular basis, indicating low frequency fires before settlement. The fact that these large fires did not occur locally prior to human colonisation reflects the inefficiency of lightning as an ignition source in New Zealand, due to the torrential rain that accompanies it, as previously discussed. This increase in fire activity due to an effective ignition source eventually resulted in near complete deforestation of the east coast of the South Island (Burrows 1960, Molloy *et al.* 1963, Cameron 1964, Molloy 1977, McGlone 1978, Burrows 1983, McGlone 1983, Bussel 1988, McGlone 1989, McGlone *et al.* 1994, McGlone and Basher 1995, Elliot *et al.* 1997, Wilmshurst *et al.* 1997, Newnham *et al.* 1998, Ogden *et al.* 1998, McGlone and Wilmshurst 1999b, 1999a, Holdaway and Jacomb 2000, Hall and McGlone 2001, McGlone 2001, Stevenson *et al.* 2001).

Contrary to the hypothesis put forward by Trotter and McCulloch (1984) Caughley (1988) and Guyette *et al.* (2003), suggesting that there was a latitudinal trend in settlement time as people moved southwards across New Zealand, my data indicate that this sudden change in fire activity occurred simultaneously throughout the South Island, at around 700 years b.p., assuming that the date from Glendhu is a result of reworking, This is in general agreement with Green (1975) Bellwood (1979) and Davidson (1984).

The combination of both charcoal and pollen changes signifies that fire was the main cause of deforestation (Byrami *et al.* 2002). Based on the rate of charcoal deposition prior to vegetation change in all four cores, and the archaeological evidence of human occupation, these fires were primarily the result of human interference rather than climate change (McGlone *et al.* 1995, Stevenson *et al.* 2001, Turney *et al.* 2001). This has resulted in overall agreement within the science community that Polynesian fires resulted in widespread deforestation (Molloy *et al.* 1963).

European influence was uniform throughout the South Island, due to high mobility of people and their land management technologies, resulting in no detectable difference between Otago and Canterbury, or, coastal and inland sites. The arrival of European settlers is most notable for the occurrence of exotic plant species for the first time, including pasture grasses, agricultural weeds and *Pinus radiata,* as a result of intensive farming (McGlone and Bathgate 1983), coincident with declines in *Pteridium esculentum* and *Gaultheria* as a result of further increased fire frequency and other land management practices. Although most of the Otago region would have been de-forested by the time Europeans arrived, extensive, purposeful burning associated with farming practices (McLeod and McLeod 1977) would have been responsible for the further extension of grasslands. These many fires would probably have eroded small patches of bush gradually, due to the higher water content associated with the remaining forested land in moister micro-sites in the landscape. The fire frequency would have increased because it was such an effective way of clearing land and of encouraging new pasture growth (McLeod and McLeod 1977). Vegetation in the Canterbury area was more intact, although substantially degraded, by the time Europeans arrived. With a conscious effort to clear land for farming purposes, the remaining vegetation was quickly destroyed.

This increase in fire regime brought about by farm management practices at the time, resulted in the initial removal of woody vegetation and shrublands, allowing early successional grasslands and fern-lands to dominate the landscape from which they were previously excluded. Continued moderate disturbances, like ploughing and grazing, prevent re-estrablishment of woody vegetation. These fine grass and fern fuels, with low moisture levels in the summer, are easily burnt and when they do so, they have highly efficient combustion that results in fewer larger particles and more small particles per unit biomass burned, which is clearly shown in the Otago sites after the first major fire event, but did not occur in Canterbury until after European arrival.

4.3.2 Variation in pollen species

Changes in the pollen profiles occurred dramatically over a very short time period at the Otago sites, with increases in herbaceous vegetation, *Poaceae, Coprosma, Gaultheria, Centrolepidaceae, Empodisma, Cyperaceae* and *Pteridium esculentum* all increasing rapidly immediately after Polynesian arrival, suggesting that there was significant deforestation very shortly after Polynesian arrival. These changes in the Canterbury sites were comparatively slower and herbaceous species did not start to dominate the pollen profiles until after European arrival. Thus, even though fire activity had noticeably increased after Polynesian colonisation, deforestation only occurred due to increased effort of burning due to farming practices to try and stimulate pastures and increase effective grazing land. This delayed change is also shown by *Nothofagus* subg. *Fuscospora* whose numbers did not begin to decline in Canterbury until after European arrival, compared with the sudden decline in *Nothofagus menziesii* abundance in Otago despite the immense distances that *Nothofagus* species can disperse. This result suggests that fires did not just destroy the local habitat but converted the entire Otago region shortly after Polynesian arrival.

Low trace levels of *Nothofagus menziesii* reflect the immense distance that Nothofagus pollen can travel and could be the result of *N. menziesii* blowing over from the west coast

The low levels of herbaceous species *Poaceae, Coprosma, Gaultheria, Centrolepidaceae, Empodisma, Cyperaceae* and *Pteridium esculentum* prior to Polynesian arrival in all four cores reflect the fact that grasses were restricted to limited areas, most probably above the tree-line or in small clearings caused by natural disturbances (McGlone 1989).

4.4 Hypothesis

Changes in pollen composition after Polynesian arrival at both Otago sites are sudden and, like changes in charcoal values, show a clear transition point. The sudden decline in *Nothofagus menziesii, Prumnopitys taxifolia Halocarpus* and *Phyllocladus,* and subsequent increases in *Poaceae, Cyperaceae, Pteridium esculentum* and *Empodisma* pollen species adapted to a high disturbance regime, suggest that deforestation in the Otago region was very rapid. However, it has been suggested that wholesale destruction of lowland forests by fire did not occur until a couple of hundred years after human arrival (McGlone and Bathgate 1983). Although this appears to be the case in the Canterbury sites, changes at the Otago sites are immediate, considering the dry condition at the time, up to 30 % drier than present (McGlone *et al.* 1997), and high fuel continuity, as a result of extensive fire-free periods in which fuel could accumulate (Maissurow 1935, Olson 1963, Dodge 1972, Meentemeyer 1978, Rundel and Parsons 1979, Harmon *et al.* 1986, Tolonen and Turunen 1996, Klarqvist *et al.* 2001a). The probability of large catastrophic fires immediately after colonisation is extremely high (Rowe and Scotter 1973, Romme 1982, Clark 1988b, Kershaw *et al.* 1994, Stocks and Kauffman 1994, Zepp and Macko 1994, Baker and Kipfmueller 2001, Schwilk 2003). It is unlikely that a culture that used fire could do so without causing catastrophic crown replacing fires in an environment in which high seasonality (summer föhn winds) results in warm, dry windy weather that would greatly increase fire spread and intensity (Romme 1982). This leads to the hypothesise that shortly after Polynesian arrival, near-complete deforestation occurred in Otago as a result of a small number of catastrophic fires that burnt unrestricted for weeks or months on end, and possibly even preceding human arrival in some areas. This scenario may be hard to imagine from the form of present-day forest vegetation, because forest is now restricted to wetter geographical areas. It has to be remembered that the moist nature of these localities is the very reason why remnant forests are still standing today and thus their environment correlations are not likely to be representative of their pre-settlement, pre-fire environments.

On arrival in New Zealand, Polynesians set about quickly exploring their new home in search for key resources, such as food, and stone (pounamu green stone) which were valuable resources. Thus fire activity throughout the South Island simultaneously occurred approximately 700 years ago.

Although changes in charcoal abundance indicate a distinct time of arrival and first fires, pollen indications of de-forestation (*Poaceae, Cyperaceae Pteridium esculentum* and *Empodisma)* show that loss of forest cover in Canterbury occurred more gradually. This delayed response reflects the inability of the Canterbury climate to allow burning due to higher levels of precipitation. One must therefore conclude that fires in Canterbury, after Polynesian arrival, were smaller and return time was still substantial, allowing woody vegetation to re-establish in the interim.

After European arrival, no signs of woody taxa re-establishing were evident, in any of the cores, suggesting repeat fires were frequent enough to prevent successional pathways from progressing far.

Chapter Five

Conclusion

Climate is instrumental in determining local and regional fire regimes due to its effect on fuel moisture, ignition and fire spread. Climatic differences between the Otago and Canterbury sites resulted in substantially more charcoal being detected in the two Otago sites before and after human colonisation, and different rates of deforestation after Polynesian arrival.

Climatic variations in precipitation and evaporative processes through time resulted in changes in charcoal abundance from changes in vegetation type, mean (summer) moisture content and thus flammability. These changes over time, within different zones, were correlated through all four cores, and thus these changes reflect large-scale climate changes.

The arrival of Polynesians, who provided a reliable ignition source, resulted in fire activity increasing simultaneously throughout the East Coast of the South Island, approximately 700 years b.p and point to a rapid dispersal immediately after arrival. Consequently there is no detectable geographical pattern in charcoal and pollen profiles associated with movement of settlers southwards across the island. European arrival resulted in further increases in fire regimes throughout the East Coast, due to farming management practices that where used to encourage pasture growth and to increase usable land.

Particle size is an important determinant of how far individual particles can be carried and thus the area which is theoretically being sampled from peat bog. The use of > 250 μm particles is the most useful size class, due to time efficiency and accuracy of analysis. This size class should be employed in further research regardless of the aims, as a higher number of widely dispersed cores sampled would create a better regional picture than a low number of cores in which the actual source of smaller charcoal particles is unclear. Thus I would like to recommend the use of > 250 μm in many cores instead.

The use of digital imagery is extremely promising and in this study has been successfully adapted to suit New Zealand conditions. It has potential to become an integral part of charcoal analysis. The increased resolution achieved through continuous sampling made immense improvements on interpretations and improved understanding of the historical sequence of environmental change.

Positive correlations between computer assisted counts and previous pollen slide charcoal occurred. However the best correlations between pollen slide counted particles and sieved particles occurred between substantially different particle sizes, indicating the significant level of fragmentation that occurs in preparing pollen slides and thus sampling via pollen slides it is not recommended as a reliable method for interpreting regional fire history.

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