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# Holocene vegetation history of a high-elevation (1200 m) site in the Lake Heron Basin, inland Canterbury, New Zealand


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### Introduction

The Canterbury high country is a favourable location to examine climate-change histories because it lies in the lee of the Southern Alps. This causes the area to be a rain-shadow region and it is sensitive to changes in the strength and persistence of the regional westerly flow. Strong westerly flow is associated with droughts and high summer temperatures. In contrast, weakened westerly flow allows moisture from the east to penetrate these upland basins. As a consequence, this is an important area to study changes in the Southern Hemisphere westerly winds in this sector of the Southern Ocean. This record is unusual because it comes from near the natural tree line and as a consequence should be particularly sensitive to climate change and other environmental forcing. There are a number of significant palaeoecological questions that relate to this setting, including: (1) the persistence of montane podocarp woodland dominated by *Phyllocladus* and *Halocarpus* into the Holocene and the timing and cause of its subsequent replacement by beech forest; (2) the role played by fire in controlling vegetation structure and species composition; and (3) human impacts in the high country, especially with the transfer of high-country land into the conservation estate and consequential issues of ecological and landscape management (Armstrong et al. 2005).

## Site description

### *Geology and physiography*

The Lake Heron basin is a 30 km long, 7-8 km wide inter-montane basin in the mid-Canterbury region between the Arrowsmith Range to the west and the Mount Somers Range to the east. It has a mean floor elevation of about 700 m amsl. The basin formed between the Canterbury front ranges and the main ranges of the Southern Alps and is the product of reverse and back thrusting (Pettinga et al. 2001) in the Quaternary. Several active thrust faults occur in the basin (Oliver and Keene 1990). The regional bedrock is Triassic Torlesse greywackes, but there are localised outcrops of both Jurassic volcanics (andesites) and Tertiary sedimentary rocks, the latter mainly in fault-angle depressions (Oliver and Keane 1990).

Staces Tarn (NZMS 260 J35/581516) is a shallow (<1 m deep) mesotrophic lake situated in a trough on a ridgeline 1.5 km south of Staces Hill (1479 amsl) at the confluence of the Cameron Valley and Lake Heron Basin (Figure 1). Staces Tarn is approximately 130 m long and 30 m wide and occurs at 1200 m (amsl). The tarn has no outlet, as a moraine impounds the lake along its southwest margin.

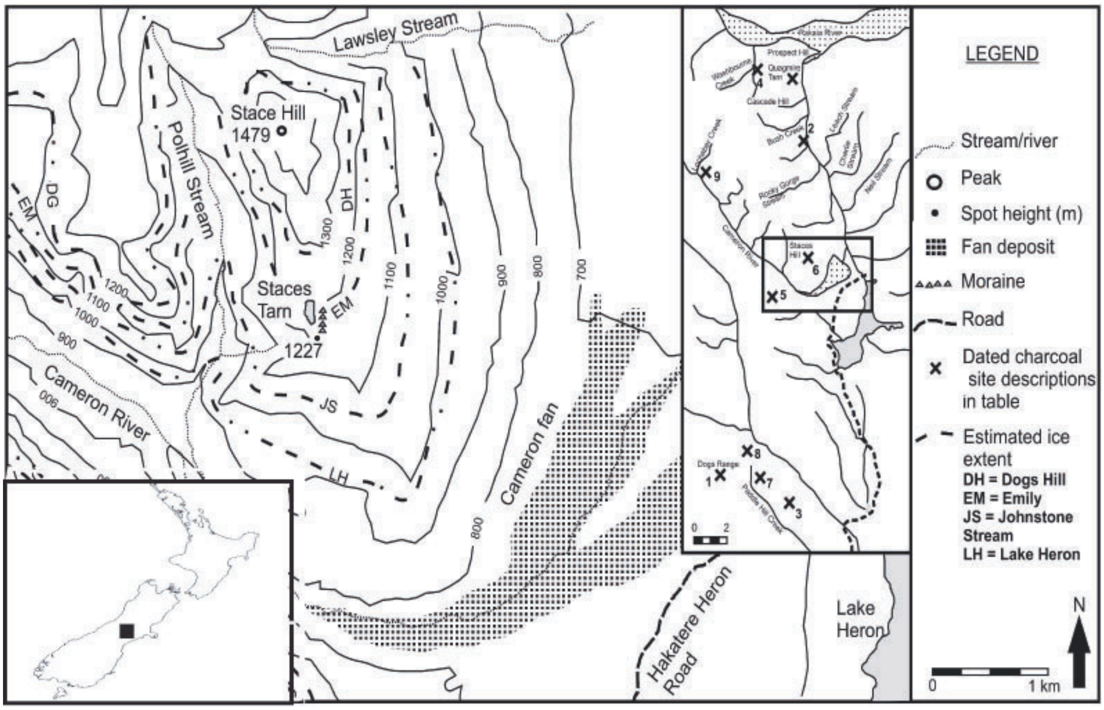


**Figure 1.** Location map for Staces Tarn. The inset map of New Zealand shows general location in the central South Island. The regional map marks on sites mentioned in the text and the other regional localities for dated charcoal occurrences. The main map details the area around Staces Tarn. The dashed lines relate to former glacial limits as defined by Mabin (1980). All advances except Dogs Hill are presumed to be last glacial cycle in age (<75 ka). Dogs Hill is attributed to oxygen isotope stage 6

The study area has experienced multiple glaciations (Mabin 1980; Pugh 2008) inferred to extend through at least three glacial-interglacial cycles, and at its maximum extent during the last glaciation ice was thick enough to overrun Staces Tarn. The tarn formed following the retreat of a small offshoot of ice from the main Lake Heron ice lobe about 18,000 years ago, dammed behind the end moraine as the glacier stagnated (Pugh 2008).

### *Climate*

The area has mild summers and cool winters and frosts are common. The mean annual rainfall at Upper Lake Heron Station is 1047 mm (1969-1981), with the mean monthly rainfall varying from 46 mm in February to 119 mm in August (Bowden 1983). Mean monthly temperatures are not available for the study area. They would be comparable to those of the adjacent Rakaia valley to the east, which range between 3.5°C (July) and 15.3°C (January) at 364 m amsl (some 836 m below Staces Tarn) (New Zealand Meteorological Service 1983). Using an environmental lapse rate of 6˚C/km, mean January temperature at Staces Tarn would be approximately 10.3°C.

### *Vegetation*

Forest cover would have been extensive below the tree line, but natural fires, Polynesian burning and European clearing have removed most forest patches except where they have survived in protected gullies. The present vegetation cover in the Lake Heron basin is predominantly tall tussock grassland, dominated by *Chionochloa* sp. cf. *rigida* (Burrows and Russell 1990). Snow tussock grassland is extensively developed on hill summits and ridges (Bowden 1983), including around Staces Tarn. There are few native trees in the study area, other than isolated stands of *N. menziesii* (silver beech), *Hoheria lyallii* and *Sophora microphylla* (Burrows and Russell 1990). Burrows and Russell also noted patches of *Kunzea ericoides* and *Leptospermum scoparium* occurring near where the Cameron River valley enters the Lake Heron basin.

Previous pollen studies and historical accounts from the Canterbury foothill country indicate that podocarp forest, typically dominated by *P. totara, P. halli* and *Prumnypitys taxifolia,* was widespread on the valley floors and lower elevation slopes (e.g. Burrows 1977). *Nothofagus* (southern beech) forest, mostly comprising mountain and silver beech (*N. solandri* var *cliffortioides* and *N. menziesii*), cloaked upper slopes below the tree line, and tussock grassland and sub-alpine herbfeld dominated above the tree line (Moar 1971; McGlone 1988).

The arrival of *Nothofagus* forest is a relatively recent phenomenon in the Canterbury hill country (e.g. Burrows and Lord 1993), with montane podocarp forest dominated by *Phyllocladus* spp. and *Halocarpus bidwilli* occupying the near-tree-line ecotone in the earlier part of the Holocene. The time of arrival of *Nothofagus* forest varies from area to area. In this area, Burrows et al. (1990) dated the burial of a *Phyllocladus alpinus* woodland by outwash in the Cameron valley to 9520 ± 95 yr BP (NZ 688). Based on dated macrofossils, *Phyllocladus* was still present in the Cameron valley below approximately 1100 m until at least 2840 ± 70 yr BP (NZ 1880; Burrows and Lord 1993).

Isolated stands of *N. menziesii* currently occur in tributary valleys in the north of the basin, the closest being located in Rocky Gorge Stream, 5 km north of Staces Tarn. Other stands to the north occur in Bush Creek, in an unnamed valley below Cascade Hill and in Downs Hut Stream. They also occur in tributaries in the east of the basin in Leach Stream, Charlie Stream and Neil Stream (Burrows and Russell 1990).

Staces Tarn has not been investigated previously and it is an excellent site for palaeoclimate studies because it is located just below the regional tree line and hence should be very sensitive to environmental changes. In this paper, we present results from a detailed pollen analytical study of the site supported by limited AMS radiocarbon and luminescence dating, to provide a Holocene vegetation and fire history for this site.

## Methods

The core was recovered from the margin of a delta at the northern end of the tarn (see Figure 2). A hand-operated D-section corer with a 50 cm x 8 cm chamber was used for core extraction. The samples were extracted alternately from two holes approximately 50 cm apart to allow for complete core recovery and to minimise down-hole contamination. The material changed from an organic gyttja at the top to a compacted grey clay with increasing depth. Sampling ceased at a depth of 193 cm as the corer was unable to penetrate further. Locations and elevations were determined using a handheld Garmin GPS Etrex H and a 1:50,000 scale topographic map.

**Figure 2.** Panoramic view of Staces Tarn. The core came from the margin of the delta at the north end of the lake

Description of the core follows Troels-Smith (1955). Sixteen 1 $cm^3$ sub-samples were removed at 10 cm intervals for the top 1 m of core, and at 20 cm intervals from 110 cm to 190 cm, for pollen analysis. The remainder of the cores was wrapped in plastic film and archived in a refrigerator at the Department of Geological Sciences, University of Canterbury. Pollen slides were prepared following the standard methods outlined in Moore et al. (1991). A lycopodium tablet added to each sample allowed the calculation of pollen concentrations. Counting was done at 400x magnification using a Leitz Diaplan comparison microscope. Palynomorphs were identified using the pollen atlas of Moar (1993) and publications by Pocknall (1981) and Large and Braggins (1991). A target of 250 dryland pollen grains for each sample was attempted but the grey silts of these cores are not pollen rich. Individual counts ranged from 52 to 306 dryland grains, with low values in the top and bottom three to four samples. Total palynomorph counts ranged from 260 to 712 per sample.

Charcoal abundance and volume are estimated through the counting of charcoal particles in a predetermined area using a fixed and random number of points, as described by Clark (1982). Charcoal values are presented in pollen diagrams as surface area per unit volume.

A pollen diagram was constructed using the PSIMPOLL program (Bennett 2002).

### *Chronology*

A sample block of inorganic lake muds was removed at 160-170 cm core depth, wrapped in tin-foil and tape, then submitted for luminescence dating to the Victoria University, Wellington, luminescence laboratory. The VUW laboratory used the multiple aliquot-additive dose technique (MAAD) for Infra-Red Stimulated Luminescence (IRSL) on the 4-8 micron polymineralic fraction in these muds. A 14.8 g charcoal sample was removed from a significant charcoal band at 76 cm depth and sent to the Rafter Radiocarbon Laboratory at GNS Science, Wellington, New Zealand, for AMS radiocarbon dating.

## Results

### *Chronology and sedimentation rates*

The luminescence sample (ST 160-170) yielded an age of 7.65 ± 0.55 ka, while the radiocarbon sample (NZA 29676) at 76 cm yielded an uncalibrated age of 4644 ± 40 yr BP (5475-5298 cal yr BP [p>.95] (using Calib 5.0: Stuiver and Reimer 1993)).

With the exception of the top 15 cm of the sample, which is rich in organic material and poorly compacted, the sediments are uniform lake muds, and sedimentation rates can be constructed from the dated charcoal layer at 67 cm depth, yielding a date of 5475-5298 cal. yr BP and the luminescence age of 7.65 ± 0.5 ka from 160-170 cm depth. This yields rates of about 0.4 mm/yr in the lower part of the core and about 0.1 mm/yr above the charcoal layer at 67 cm. These rates are extremely slow by New Zealand standards. The unconsolidated material in top 15 cm is clearly historical (based on palynolomorphs – see below) and there is a possibility of loss or disturbance of material at this level, due to animal trampling and/or episodic desiccation. The arrival of beech in the pollen record at 20 cm suggests that this is unlikely to be significant.

### *Pollen results*

Figure 3 displays the concentration of dryland taxa without swamp elements and fern spores.

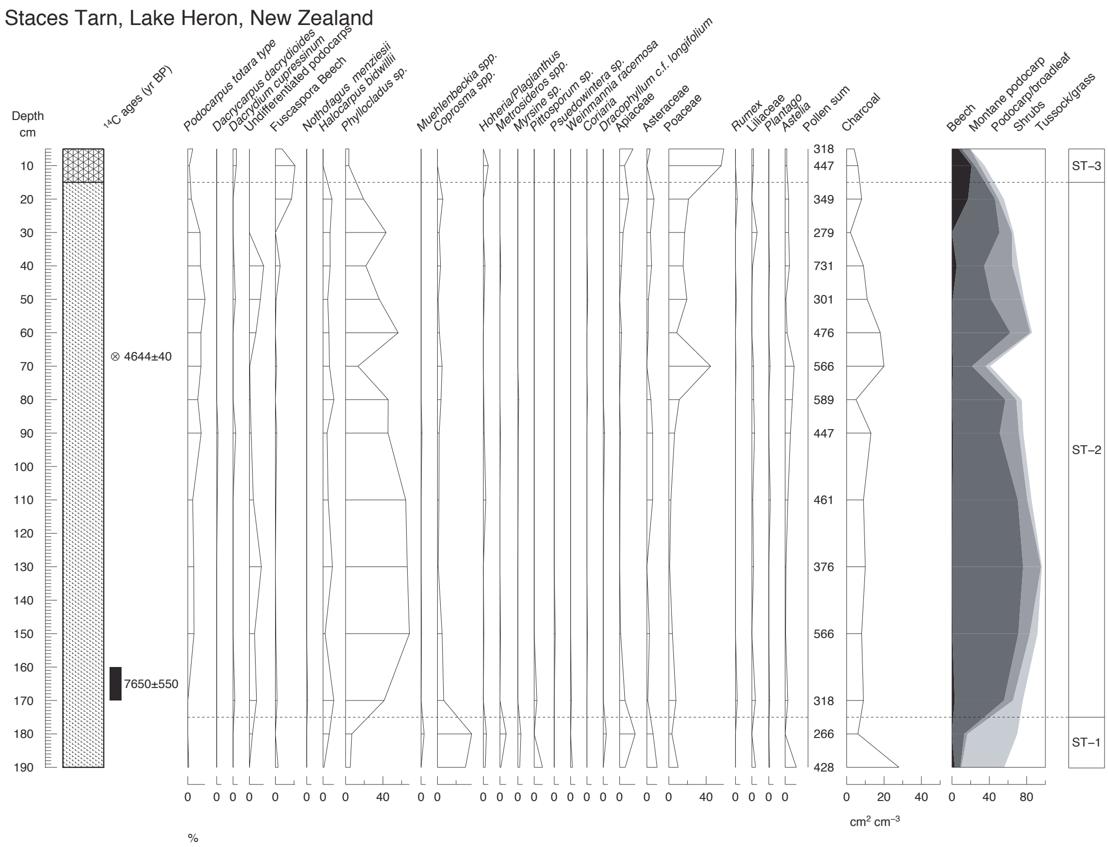


**Figure 3.** Summary pollen diagram for Staces Tarn. Note that the older age is a luminescence age, while the younger age is a radiocarbon result. The pollen sums are the total counts; dryland totals are lower

The dryland pollen results are presented in the diagrams in five summary groups.

1. Beech forest, consisting of *Nothofagus* fuscaspora type, a composite taxon of five indistinguishable beech species, and *Nothofagus menziesii.* We include *Peraxilla* sp. with the beeches as this mistletoe is usually a parasite on beech (Allan 1961).
2. Montane podocarp forest, which consists of *Halocarpus bidwillii*, *Phyllocladus* spp. and *Podocarpus nivalis.* These taxa can occur as forest trees, as heathland elements, or even as prostrates.
3. Podocarp/broadleaf forest, consisting mainly of *Podocarpus/prumnopitys* type, *P. totara* type (represented by both *P. hallii* and *P. traversii),* and small counts of *Dacrycarpus dacrydioides*, *Dacrydium cupressinum,* and other lowland forest types. This forest type occurs mainly below 500 m and is relatively diverse botanically, especially in the underrepresented broadleaf elements. Podocarp pollen grains that were unidentifiable due to damaged sacchi or corpus are included in the total count as 'undifferentiated podocarps'.
4. Shrubland: small trees and tall shrubs dominated in the pollen records by *Coprosma*, with *Muehelenbeckia* spp., *Hoheria* sp., *Myrsine* spp. and *Pseudowintera* sp. and the forest margin/disturbance indicator *Coriaria.*
5. Tussock grasses, heaths and herbfeld, comprised mainly of Poaceae (grasses), with smaller contributions from Apiaceae, *Gentiana, Dracophyllum,* Asteraceae, Liliaceae, and *Astelia.*

We also counted but do not present wetland taxa consisting of Cyperaceae with Restionaceae, *Phormium* (flax), *Myriophyllum,* Chenopodiaceae and *Potamogeton.* Trilete and Monolete fern spores, the most common palynomorphs, were included in this group, as ferns were concentrated around the lake margin.

European disturbance indicators and pasture weeds, including *Rumex* and *Plantago*, are noted, and *Rumex* is common enough to warrant presentation as a curve. Other than *Rumex,* European weeds were present in only trace amounts.

## Zone ST-1: 190-175 cm. *Coprosma* with *Gentiana*, Apiaceae, Asteraceae and *Astelia* zone

*Coprosma* varies between 30% and 35%, with *Gentiana* decreasing from 10% to 5% at the top of the zone. Of the tussocks and grasses, Apiaceae, Asteraceae and *Astelia* fluctuate between 5% and 15%. Poaceae comprises 10% of the dryland total. At the base of the zone, almost 0.03 $cm^2/cm^3$ of charcoal content is recorded, the largest count in the core.

### *Zone interpretation*

Zone ST-1 is characterised by the dominance of shrubs and herbs (*Coprosma, Gentiana,* Apiaceae, Asteraceae, *Astelia*). The pollen assemblage of ST-1 represents a heathland environment, comprising shrubs and herbs that are typically slow growing or stunted. Heathland occurs in the South Island in mountainous areas and on glacial outwash surfaces, including wet areas above the tree line. Coprosmas occur in a range of environments, including sub-alpine landscapes, and are tolerant of both poorly drained and exposed habitats (Macphail and McQueen 1983). While the shrubs range from lowland to montane/sub-alpine, they tend to be common in records from cooler and higher-elevation sites. *Dracophyllum* is a member of the Ericaceae and most taxa display typical heath morphologies, except the tree-lily-like *D. traversii* (mountain neinei). Most are montane to sub-alpine in distribution and *D. longifolium* is very common in the modern vegetation around the core site. It is severely underrepresented in pollen diagrams (Macphail and McQueen 1983). Gentians, Apiaceae and the dreaded Astelias (Spaniard) are typical elements of sub-alpine grassland and herbfield vegetation in New Zealand (e.g. Wardle 1986). They normally indicate either above-tree-line or frost-basin-type environments. All of these taxa are indicative of a near-tree-line setting, with the site inferred to sit above the tree line at this time.

Two anomalous pollen grains occur in ST-1. The first is *Peraxilla* sp. of the genus Lorantheaceae, one of the three New Zealand beech mistletoes. *P. tetrapetala* is an arboreal xylem parasite dependent on its host for water and nutrients (Ullmann et al 1985). The parasite is commonly found on *Nothofagus* spp., but it has been recorded also on *Quintinia* (Allan 1961). These mistletoes are usually dependent on birds for pollination, although insects may play a role for some species (Kuijt 1969). The presence of mistletoe indicates that beech trees may have been growing near Staces Tarn at this time or the grain may have washed off a bird. However, the second anomalous grain is that of a *Brassospora* beech. Given that this pollen group has been extinct in New Zealand since the mid-Pleistocene (Mildenhall and Biryami 2003), it is likely that it is derived from Tertiary sediments that outcrop at lower elevations in the Cameron valley (Warren 1967) and which may have outcropped upstream of the tarn.

## Zone ST-2: 175-15 cm. *Phyllocladus* and lowland podocarps zone

*Phyllocladus* dominates the zone, varying between 25% and 70% of the total dryland taxa. *Podocarpus/Prumnopitys* type increases from 1% at the bottom of the zone to 17% at the top, while undifferentiated *Podocarpus* pollen fluctuates between 2% and 15%. Low counts of *Dacrycarpus dacrydioides* (1%) and *D. cupressinum* (3%) occur. Shrubland taxa have very low counts; *Coprosma* decreases from 7% to 2% upwards through the zone. The grasses Apiaceae and Poaceae fluctuate between 1% and 5%. Asteraceae and *Astelia* increase from 1% to approximately 7% at the top of the zone. The charcoal content fluctuates between 2 and 6 $cm^2/cm^3$.

Within Zone ST-2 at 70 cm depth, Poaceae increases briefly to 47%, with *Phyllocladus* declining to 10%. *Podocarpus* types remain much the same, at 12%. *Astelia* increases slightly to 9%. Microscopic charcoal content at this depth peaks at approximately 0.02 $cm^2/cm^3$ and remains elevated at 65 cm depth. At 67 cm depth, a 2 mm thick band of macroscopic charcoal occurs.

Zone ST-2 is characterised by the dominance of celery pine *Phyllocladus* spp. It is interpreted as a montane podocarp forest. Now, *Phyllocladus* forest occurs in regions with an annual precipitation of at least 1250 mm (Wardle 1969), suggesting that the region was wetter than at the present day. As the floor of the Lake Heron basin currently receives around 1000 mm rain per year, it probably indicates relatively similar conditions to today, though it may have been marginally wetter.

The lowland podocarps are abundant pollen producers and have long-distance dispersal capabilities. They do not currently occur much above 600 m elevation and therefore are unlikely to have ever occurred close to Staces Tarn, so they provide a measure of the regional pollen rain. *D. cupressinum* is a widespread taxon but is more common in the wetter western regions. *D. dacrydioides* is widely distributed on the West Coast of the South Island, and is not currently found in inland Canterbury (Lintott and Burrows 1973). It currently occurs in lowland forests, dominating fertile, free-draining floodplains and the wet margins of the lowland swamps and bogs (Metcalf 2002). *Casuarina* is another taxon that is extinct in New Zealand. Unlike Brassospora beech, it is a persistent but rare component of New Zealand pollen diagrams and is interpreted as being derived from Australia. It confirms the strong westerly sourcing of long-distance-derived pollen in Staces Tarn.

There is a gradual decline in *Phyllocladus* in the top half of this zone, matched by a gradual increase in grass (Poaceae). There are also generally higher levels of charcoal in the upper half of the zone and there is a macroscopic charcoal layer at 67 cm depth.

This spike in grass is short lived and tree and shrub values recover to near pre-fire values by 60 cm, even though this is the peak microscopic charcoal level. We infer the relationship between *Phyllocladus* and grass to represent changes in either the structure of the woodland (becoming more open) or proximity to a grassland woodland boundary.

### Zone ST-3: 15-0 cm. Fuscaspora type and Poaceae zone

*Nothofagus fusca* type increases to 15% before dropping away to 7% in the uppermost zone. Poaceae is the other dominant taxa and increases from 20% to almost 60% at the top of the zone. *Hoheria* peaks at 5% and Apiaceae fluctuates between 6% and 15%. Asteraceae, Liliaceae and *Astelia* decrease slightly to 2%. *Phyllocladus* decreases from 15% to 2%, while *P. totara* type fluctuates between 1% and 5% and *D. cupressinum* is 4% of the dryland taxa. Charcoal values decrease upwards through the zone from 0.006 to 0.004 $cm^2/cm^3$.

Zone ST-3 is characterised by the emergence of Fuscaspora beech tree pollen, which we attribute to mountain beech *Nothofagus solandri* var *cliffortioides* based on site elevation and proximity to the tree line. Silver beech (*N. menziesii*) and mountain beech are the most common taxa of near-tree-line assemblages in this region and *N. menziesii* pollen is easily distinguishable from the other beech pollens. In addition, *Phyllocladus* is replaced by grass and Apiaceae. We infer two changes, firstly the invasion of beech into already declining *Phyllocladus* woodland, and secondly a general opening up of vegetation, with grassland becoming widespread. The former is natural, with similar expansions of *Nothofagus* forest recorded in many pollen diagrams in Canterbury (Moar 1971; Lintott and Burrows 1973; Russell 1980; Burrows and Russell 1990) and elsewhere in New Zealand. The latter is evidence for human impact, and specifically, European settlement.

## Discussion and conclusions

### *Holocene vegetation history of Staces Tarn and Lake Heron area*

Vegetation in the lowest zone (ST-1) is characterised by the dominance of shrubs and herbs and is typical of a late-glacial-period pollen record from inland Canterbury (Burrows and Russell 1990). We have no age control in this zone and we cannot discount the alternative possibility that it could be early Holocene in age. We note that near-Holocene temperatures were reached in many parts of eastern New Zealand by about 14,000 years ago (Turney et al. 2003). An early-Holocene thermal optimum, between 1.5°C and 3°C warmer than present, is suggested for the New Zealand region from about 9000 to 7000 yr BP (Weaver et al. 1998; Wilmshurst et al. 2007).

At Prospect Hill (13 km north and 470 m lower), low-montane forest replaced shrubland at 10,000 yr BP. However, forest arrival at Staces Tarn challenges the presumed early-Holocene warmer temperatures, as trees are not dominant at the site until 7500 yr BP. Podocarps disperse and colonise sites quickly if conditions are favourable (Macphail and McQueen 1983) and it would have been expected that podocarps would have colonised the site earlier in the thermal optimum. Hence, some other factor or factors must have been inhibiting forest spread. The upper limit of tree growth has long been associated with the summer 10°C isotherm (e.g. Koeppen 1923), and West (1977) noted that at least three months with mean temperatures greater than 10°C are required for forests to dominate. Small changes in the mean monthly temperatures could result in noticeable changes in vegetation structure. It is proposed that low seasonality during the early Holocene resulted in cooler summers, and delayed the forest colonisation of the high-elevation Staces Tarn area. This is despite the fact that mean *annual* temperatures were at least as warm as they are today.

As climates became more seasonal and summer temperatures rose, we infer that montane podocarps spread uphill, reaching the site about 7700 radiocarbon years ago. They remained dominant until about 5000 yr BP. After this time, they steadily declined coeval with a gradual increase in grasses. McGlone and Wilmshurst (1999) suggested that as the subtropical high retreated northwards from its early-Holocene position, temperatures gradually declined. The westerlies also increased through the Holocene (Shulmeister et al. 2004) and the gradual decline of podocarp forests may reflect both a gradual cooling, and more significantly, an increase in the occurrence of droughts as eastern areas dried out under the enhanced westerly flow.

Based on sedimentation rates, beech pollen rose from trace values after about 3000 yr BP at Staces Tarn, but it was not until about 1500 yr BP that a pronounced pollen change occurred as beech replaced the montane podocarp forest as the dominant forest cover. The beech history at Staces Tarn is similar to adjacent areas. Beech pollen was present at Prospect Hill in the Rakaia Valley to the north at approximately 4500 yr BP. However, it was not until after 2000 yr BP that *N. fusca/N. menziesii* became the dominant forest type (Burrows and Russell 1990) at that site. In the southeastern South Island, *Nothofagus* forest expansion occurred around 2500 yr BP (Pocknall 1981).

Beech was eliminated from extensive parts of its South Island range during the glacial maximum, or earlier. Unlike podocarp forest, which is vagile, beech responded slowly to post-glacial climate change. The slow beech expansion was and still is the result of a range of factors, including slow dispersal rates, specialist soil mycorrhizal requirements (Baylis 1980), and poor competitiveness with podocarps on nutrient-rich soils (Rogers and McGlone 1989). Climate change also played a role. Cool, moist early-Holocene summer climates favoured montane podocarps over beech forest. Warmer and drier summers later in the Holocene favoured beech (e.g. Lintott and Burrows 1973). Increased disturbances caused by fire to the already weakened podocarp forests will have encouraged their replacement by beech. In short, the arrival of beech is an ecological change, but is set in the context of ongoing climate changes that favoured this change.

The very top level of the core displays a drop in beech pollen and a dramatic increase in grass pollen. This is almost certainly an anthropogenic signal relating to the opening up of the basin to grazing, which was associated with burning.

### *Fire history*

The role of fire in New Zealand vegetation history has been an issue of some debate in the New Zealand ecological literature. Lightning strikes are the only source of natural fires in the South Island and McGlone (2001) shows that the total area burned under modern conditions is very minor. Whether pre-deforestation (and pre-human settlement) trees and shrubs were more susceptible to fire is not known, but McGlone (2001) suggests that this is at least possible. Natural fires are inferred to have played a role in South Island vegetation changes in the late Holocene, and if any area in New Zealand is likely to display ecological responses to fire, the dry (rain-shadow) inland basins of Canterbury and Otago are the best candidates.

Previous research has indicated that the Arrowsmith Range and upper Rakaia Valley region has been subject to Holocene fire activity (Harvey 1974; Burrows 1983, 1988, 1996; Rodbell 1986), but there are difficulties in making correlations between events due to the variety of settings and the likelihood that only a few of many tens of fires are recorded. At Staces Tarn, a macroscopic charcoal layer in the sediment core is dated at 4644 ± 40 BP (NZA 29676) at 67 cm. Other macroscopic charcoal layers are recognised at 30 cm, 37 cm, 47 cm and 91 cm, and throughout the core there appears to be a stable concentration of microscopic charcoal fragments, indicating persistence of fire through the Holocene, albeit at low levels. Applying a steady rate of sedimentation between the macroscopic charcoal layers suggests fires occurred about 6900, 3750, 2950 and 2400 cal yr BP (rounded to nearest 50 years). For comparisons with previous studies, uncalibrated ages are more useful, and when interpolated from the uncalibrated radiocarbon age, these fires occurred at 6300, 3250, 2100 and 2100 yr BP. Sedimentation rates were previously used to estimate the ages of charcoal layers in a sediment core from Prospect Hill, in the adjacent Rakaia catchment, and yielded ages of c. 5800, 3800, 3500, 2600 and 860 yr BP (Burrows and Russell 1990). They confirm increased fire occurrence in the second half of the Holocene and are consistent with the climatological inferences.

Of significance to this study are dated charcoal fragments from Mount Pyramid (Rodbell 1986), only 3 km northeast of Staces Tarn. Two fire events at this location have been dated, at 5240 ± 110 and 2180 ± 100 yr BP (see Table 1). While the first event is not identified in the sediments at Staces Tarn, the event at ~2180 yr BP may correlate with the charcoal layer estimated to have occurred at 2100 yr BP at Staces Tarn. If this is the case, the fire must have been regionally significant given that it occurred on both sides of the Cameron River and reached high elevations (Figure 1).

**Table 1.** Buried soil horizons with charcoal from the Lake Heron area (* indicates wood sample, inferred to date a fire)

| Site number | Laboratory number | Radiocarbon date (half life 5568 yr) | Location | Grid reference, altitude | Reference |
|---|---|---|---|---|---|
| 1 | NZ 1684 | >40,900 | Dogs Range, Paddle Hill Creek | J36/525374 1340 m | Harvey 1974 |
| 2 | Wk 2637* | 8880 ± 60 | Bush Creek, Lake Stream Valley | J35/587596 660 m | Burrows 1996 |
| 3 | NZ 6810 | 6940 ± 150 | Dogs Range, Paddle Hill Creek | J36/574358 1045 m | Rodbell 1986 |
| 2 | Wk 3451* | 5910 ± 60 | Bush Creek, Lake Stream Valley | J35/587596 660 m | Burrows 1996 |
| 4 | NZ 3942 | 5830 ± 130 | Washbourne Stream, Prospect Hill | S73/637833 800 m | Burrows and Russell 1990 |
| 5 | NZ 6803 | 5240 ± 110 | Mount Pyramid, Cameron Valley | J35/559491 1580 m | Rodbell 1986 |
| 6 | NZA-29676 | 4644 ± 40 | Staces Tarn, Staces Hill | J35/581516 1210 m | This study |
| 5 | NZ 6808 | 2180 ± 100 | Mount Pyramid, Cameron Valley | J35/559491 1580 m | Rodbell 1986 |
| 7 | NZ 1686 | 1860 ± 70 | Upper Paddle Hill Creek | J36/548371 609 m | Harvey 1974 |
| 8 | NZ 1687 | 1820 ± 70 | Upper Paddle Hill Creek | J36/544392 731 m | Harvey 1974 |
| 4 | NZ 3941 | 860 ± 50 | Washbourne Stream, Prospect Hill | S73/637833 800 m | Burrows and Russell 1990 |
| 9 | NZ 3943 | 620 ± 60 | Lochaber Creek, Cameron Valley | J35/511574 1200 m | Burrows et al. 1990 |

In summary, fire is persistent in these inland basins through much of the Holocene but at a relatively low base level. There is evidence for an increase in the frequency of fire events from about 5000 yr BP and a significant increase about 3000 yr BP. McGlone et al. (1995) reported a similar time for the occurrence of fires in Central Otago. Fires in east Otago are dated to have started slightly later (McGlone and Wilmshurst 1999). Why should this pattern be apparent? As already noted, throughout the Holocene, summer insolation had gradually strengthened. This resulted in increasing summer insolation and enhanced westerly circulation, with thresholds apparently exceeded at about 5000 yr BP when the West Coast glaciers reactivated (e.g. Shulmeister 1999) and about 3000 yr BP when wet podocarp forest occupied Southland (e.g. Markgraf et al. 1992). The stronger insolation and more frequent westerly winds, especially in late summer and autumn, would have dried out the basins and made them susceptible to lightning-strike fires.

Did these fires have an ecological consequence? From the Staces Tarn record, the suggestion is yes. Unlike many areas where grass pollen becomes widespread only in post-Maori times, grass begins to increase steadily from about 5000 years ago. This is unlikely to be a lowering of the tree line for the climatological reasons outlined earlier. Instead, it reflects the gradual opening up and ultimate replacement of the *Phyllocladus* woodland. It is unlikely that this would have occurred without fire to maintain the ecological pressure on the woodlands. The arrival of beech forest may also be a direct effect of the intensified burning regime.

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