

# Earthquake impacts in old-growth *Nothofagus* forests in New Zealand

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**Abstract.** Six stands located on different land forms in mixed old-growth *Nothofagus* forests in the Matiri Valley (northwest of South Island, New Zealand) were sampled to examine the effects of two recent large earthquakes on tree establishment and tree-ring growth, and how these varied across land forms. 50 trees were cored in each stand to determine age structure and the cores were cross-dated to precisely date unusual periods of radial growth. The 1968 earthquake (M = 7.1, epicentre 35 km from the study area) had no discernible impact on the sampled stands. The impact of the 1929 earthquake (M = 7.7, epicentre 20 km from the study area) varied between stands, depending on whether or not they had been damaged by soil or rock movement. In all stands, the age structures showed a pulse of *N. fusca* establishment following the 1929 earthquake, with this species dominating establishment in large gaps created by landslides. Smaller gaps, created by branch or tree death, were closed by both *N. fusca* and *N. menziesii*. The long period of releases (1929-1945) indicates that direct earthquake damage was not the only cause of tree death, and that many trees died subsequently most likely of pathogen attack or a drought in the early 1930s. The impacts of the 1929 earthquake are compared to a storm in 1905 and a drought in 1974-1978 which also affected forests in the region. Our results confirm that earthquakes are an important factor driving forest dynamics in this tectonically active region, and that the diversity of earthquake impacts is a major source of heterogeneity in forest structure and regeneration.

**Keywords:** Dendro-ecology; Disturbance; Forest dieback; Landslide; *Nothofagus fusca*; *Nothofagus menziesii*; Population dynamics.

**Nomenclature:** Allan (1961).

## Introduction

In tectonically active regions, earthquakes can be a major disturbance agent in forests, especially in unstable areas where landsliding occurs (Veblen & Ashton 1978; Garwood et al. 1979; Stewart & Veblen 1982). Damage is caused by the shaking or shearing of tree roots along surface fractures (e.g. LaMarche & Wallace 1972; Jacoby et al. 1988; Allen et al. 1999), the uplift of the ground surface or changes in the water table (Jacoby & Ulan 1983; Jacoby et al. 1997; Van Arsdale et al. 1998). The damage may kill trees, but they often survive and retain permanent signs of the disturbance in the stem. These include fractures in the wood (Van Arsdale et al. 1998), growth suppression in the years following disturbance (Jacoby et al. 1988; Kitzberger et al. 1995; Jacoby et al. 1997; Van Arsdale et al. 1998), production of reaction wood after tilting (Page 1970; LaMarche & Wallace 1972; Meisling & Sieh 1980; Jacoby et al. 1997) or growth releases after the death of neighbouring trees (Kitzberger et al. 1995). These signs have been used to precisely date the timing of past earthquakes (Jacoby et al. 1988; 1997; Wells et al. 1999).

The intensity of damage to forests varies strongly with distance from the earthquake's epicentre. Catastrophic landslides that completely remove the forest are easily visible and the most common feature used to estimate forest damage after earthquakes (Veblen & Ashton 1978; Garwood et al. 1979), but Allen et al. (1999) showed that an earthquake's immediate impact is more widespread. Earthquake impacts also vary according to geomorphology and the climatic conditions at the time of the earthquake (Kitzberger et al. 1995; Van Arsdale et al. 1998).

In tectonically active landscapes, spatial variation in the structure and composition of forest stands may be influenced by variation in the levels of damage and the subsequent recovery of forests on sites that differ in their susceptibility to earthquake impacts. Indeed, the variation in damage that can be caused by an earthquake within a single catchment, ranging from stand-destroy-

ing landslides to minor branch breakage (Allen et al. 1999), suggests that earthquakes could be a significant source of environmental heterogeneity, maintaining canopy tree diversity by creating a range of regeneration opportunities. While several studies have documented variation in the direct impact of earthquakes on forests (see above), few have examined the resulting patterns of forest recovery to assess the extent to which this mosaic of earthquake impacts is responsible for spatial variation in forest structure and composition, and whether patterns of forest recovery are predictable from the type of earthquake damage.

In this study, we reconstruct the type of damage and the subsequent patterns of forest recovery in six forest stands located close to the epicentres of two major earthquakes that occurred in the 20th century in the north of South Island, New Zealand. We located the six stands on land forms of varying stability that were likely to have been differentially impacted by the earthquakes. The aims of our study were to: (1) reconstruct the pattern of earthquake damage in each stand; (2) compare the patterns of tree establishment and growth following the earthquakes between stands and species; and (3) contrast the impact of earthquake disturbance with other types of disturbance (storm and drought) that have affected the study area within the last century.

## Study area

New Zealand lies on the boundary between the Australian and Pacific tectonic plates, and earthquakes are frequent (Suggate et al. 1978). Recent work suggests that earthquakes are a major disturbance agent in forests across large areas of South Island (Pearce & O'Loughlin 1985; Allen et al. 1999; Wells et al. 1999). We chose the Matiri Valley (northwest Nelson, South Island) for sampling because it is situated close to the epicentre of two large earthquakes that struck the South Island in the 20th century.

The Murchison Earthquake occurred on June 17, 1929 with a magnitude of 7.7, and was the largest earthquake in South Island recorded in the 20th century (Fyfe 1929; Pearce & O'Loughlin 1985). The estimated epicentre was ca. 20 km southwest of our study area (Eiby 1968). The shaking intensities exceeded X (Modified Mercalli Intensities, Eiby 1966) over 3900 km<sup>2</sup>, and triggered hundreds of landslides within an area of 5000 km<sup>2</sup> (Adams 1981; Pearce & O'Loughlin 1985). The Inangahua Earthquake occurred on May 24, 1968, with a magnitude of 7.1 (Adams et al. 1968). The epicentre lay 35 km to the west of the study area, and it triggered landslides in a 16 km radius. No other major earthquake is historically known in the region. How-

ever, Adams (1981) suggested that Lake Matiri and seven other nearby prehistoric landslide-dammed lakes were formed simultaneously during a major earthquake about three centuries ago.

Other historic disturbances are known to have affected the region, including windstorms in 1898 (Foster 1931) and 1905 (Benn 1990), and a period of drought in the early 1930s (New Zealand Meteorological Service unpubl. data) and in 1974-1978 (Hosking & Kershaw 1985). Other local disturbances could have affected this uninhabited valley.

The lowland forests in the Matiri Valley are old-growth mixed *Nothofagus* forests, dominated by *N. fusca* and *N. menziesii* (Rose 1985). Compared to *N. menziesii*, *N. fusca* is less shade-tolerant, grows faster in the open and is more sensitive to insect attack and droughts (Wardle 1984; Hosking & Kershaw 1985).

Mean annual precipitation in the area is ca. 2400 mm, with slightly less rainfall during summer than the rest of the year (Anon. 1978, 1984b). The temperature is a little colder than the nearby town of Murchison, which has a mean annual temperature of 11.4 °C, varying between 5.1 °C in July and 17.1 °C in February (New Zealand Meteorological Service 1983).

## Methods

### *Stand selection and sampling*

In April 1999 six forest stands were subjectively chosen in the valley, along a 3 km stretch above and below Lake Matiri (41° 39' S 172° 20' E) and between 280 and 380 m a.s.l. These stands were located on land forms common in the study area, but they were likely to vary in the damage suffered during an earthquake:

- *Alluvial fan*: a stand growing on a fan (slope 10°, aspect E) at the bottom of a lateral creek.

- *Alluvial terrace*: a narrow, probably no longer active terrace, partly covered by a small alluvial fan from a lateral creek.

- *Rock slide*: a steep side slope (35°, SE) with visible stones on the ground surface.

- *Steep side slope*: (30°, SE) situated above the alluvial terrace.

- *Gentle side slope*: (20°, E) with large diameter trees giving the impression of a stable stand, without any recent major disturbance.

- *Boulder field*: on the toe of an old rock avalanche (10°, W), with boulders up to 6 m in diameter. A very irregular surface, with trees growing between or on the tops of the boulders.

We sampled trees in each stand using the point-centred quarter method (Cottam & Curtis 1956). A total

of 25 points were located at 15 m intervals along a single transect, or at the intersections of a grid, depending on the size of the stand. At each point, in each quarter we identified the closest *Nothofagus* tree > 5 cm diameter at 1.3 m (DBH) and measured its DBH. Two trees (always from the same two quarters) were increment cored at 1.3 m, one core in the direction to which the trunk was inclined, or in the upslope side for straight trees, and one core at right angles to the first (Braam et al. 1987). The canopy position of each cored tree was recorded as either canopy, subcanopy or understorey. All tree cores were mounted and sanded with successively finer grades of sandpaper, until the growth rings were clearly visible. It is generally accepted that ring formation is annual in both *Nothofagus* species (Wardle 1984).

Soils pits were dug in each stand to identify recent landslides or rockslides, and to assess water storage capacity. Several pits were dug in each stand to sample the range of soil variation, and the soil profiles were described.

#### *Dendrochronological analyses*

Tree rings on each core were measured to the nearest 0.01 mm under a binocular microscope. Both species in every stand were cross-dated separately, visually and with the computer programs COFECHA (Holmes 1983) and XMATCH98 (Fowler 1998), to detect measurement errors and missing rings. In the mesic environmental conditions that characterize the valley, cross-dating was difficult and could only be achieved with a reasonable correlation for 40.2 % of *N. fusca* and 35.6 % of *N. menziesii*, which was characterized by numerous missing rings. In each stand a master chronology was prepared for each species with the best correlated trees, and was used to date as precisely as possible the remaining cores. All cores were used in determining the age structure of the stands, but cores with long periods of early suppression (e.g., small trees under the canopy) were not used for further dendrochronological analysis.

Tree ages were determined by ring counting. For cores that did not pass through the centre of the tree, the number of missing years to the centre was estimated using the geometric model in Duncan (1989) if arcs were visible, or with the missing radius to the geometric centre for very large or rotten trees (Wardle 1963). No correction to tree ages was made for the time taken to reach coring height. However, mean ages ( $\pm$  sd) of a small sample of 1.3-m tall seedlings harvested at ground level were  $18.8 \pm 10.5$  yr ( $n = 4$ ) in gaps and  $26.3 \pm 10.3$  yr (18) in the understorey for *N. menziesii*, and  $11.0 \pm 3.4$  yr (10) in gaps and  $20.0 \pm 5.4$  yr (21) in understorey for *N. fusca*.

Dates of growth releases and suppressions were recorded for all the retained cores. In the absence of data

on specific responses to thinning, the same thresholds were used for *N. fusca* and *N. menziesii* to define periods of growth release and suppression. We recognized two types of growth release: intense and short, and moderate and long. An intense, short growth release was defined as a  $\geq 250$  % increase in mean ring width between consecutive 5-yr periods, while a moderate, long release was defined as a  $\geq 100$  % increase between consecutive 10-yr periods. Many releases fulfilled both criteria, but the intense, short releases were more typical of previously slow growing trees. All identified releases were checked to eliminate those that were an artefact of recovery following a short growth suppression (V-notches of Nowacki & Abrams 1997). We defined a growth suppression as a  $\geq 250$  % decrease in mean ring width between consecutive 5-yr periods. Canopy trees that showed a period of slow early growth were considered to have recruited into the canopy from the understorey, and the timing of that transition was identified as the first sustained release followed by normal growth. Trees with a high initial growth rate followed by normal growth were considered to have recruited directly into the canopy from a newly established seedling (Nowacki & Abrams 1997).

Earthquakes are likely to destabilize and tilt trees (LaMarche & Wallace 1972), which then respond by producing tension wood and showing eccentric growth. Cores were examined under the microscope and rings of tension wood were recorded. Tension wood can be recognized because of its darker colour and fewer and narrower large vessels (Schweingruber 1996). Eccentricity was measured following Braam et al. (1987), comparing the relationships between the annual growth along two perpendicular radii. Only trees with two well cross-dated cores were analysed for eccentricity.

## Results

### *Age structure and canopy position*

The age-class distribution of the stands (Fig. 1) shows a marked increase in *Nothofagus fusca* regeneration after 1900, with a peak around 1940 for most stands, but around 1920 for the steep and gentle side slopes. *N. menziesii* shows a more constant pattern of regeneration, with a higher proportion of older trees, and with a slight increase in regeneration after 1900 visible in only half of the stands (alluvial fan, alluvial terrace and steep side slope). Table 1a confirms this difference between species, with a higher proportion of *N. fusca* than *N. menziesii* established after 1929 in all but one stand.

We observed variation among stands in the proportion of trees that had reached the canopy after 1929

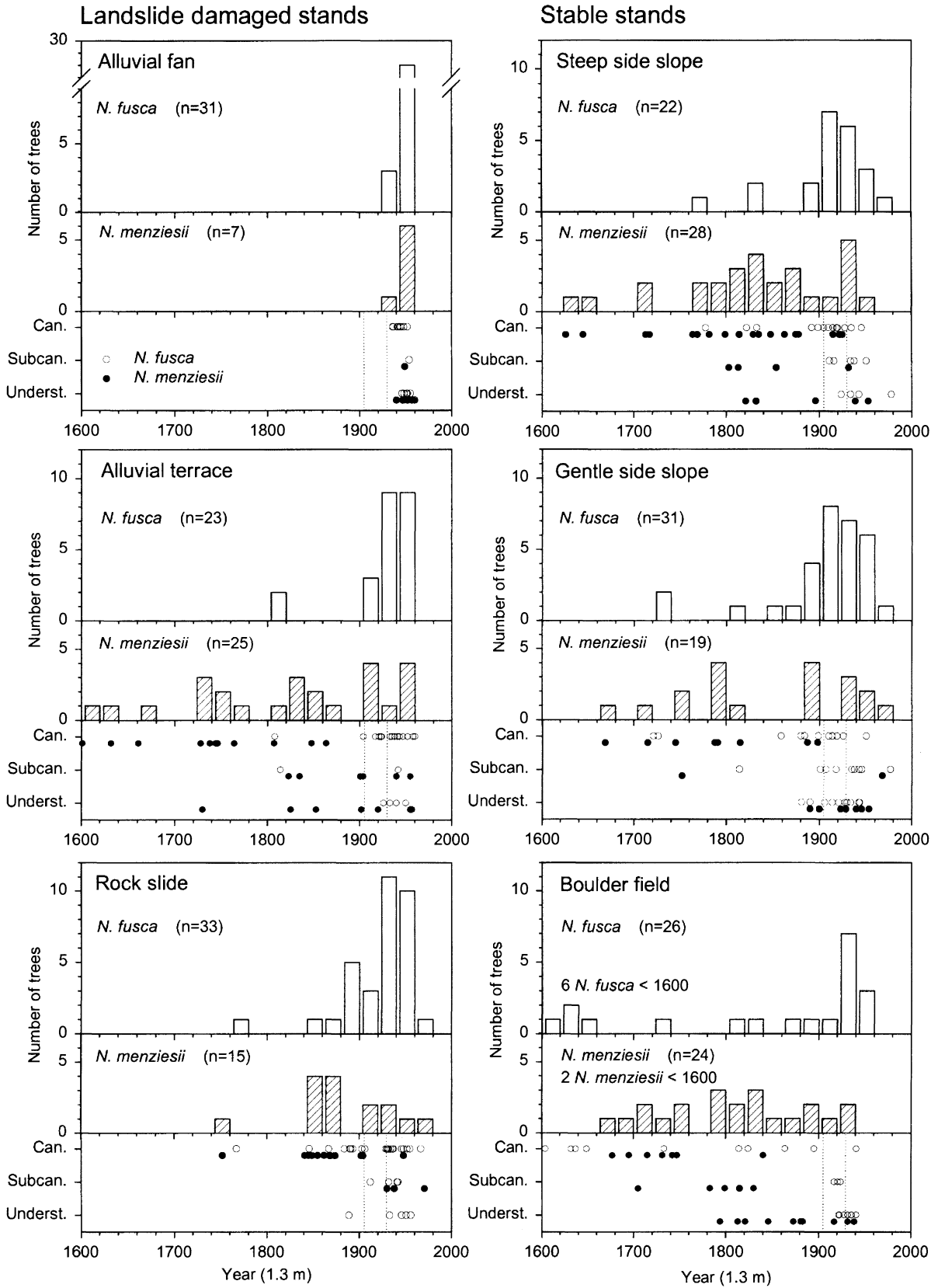
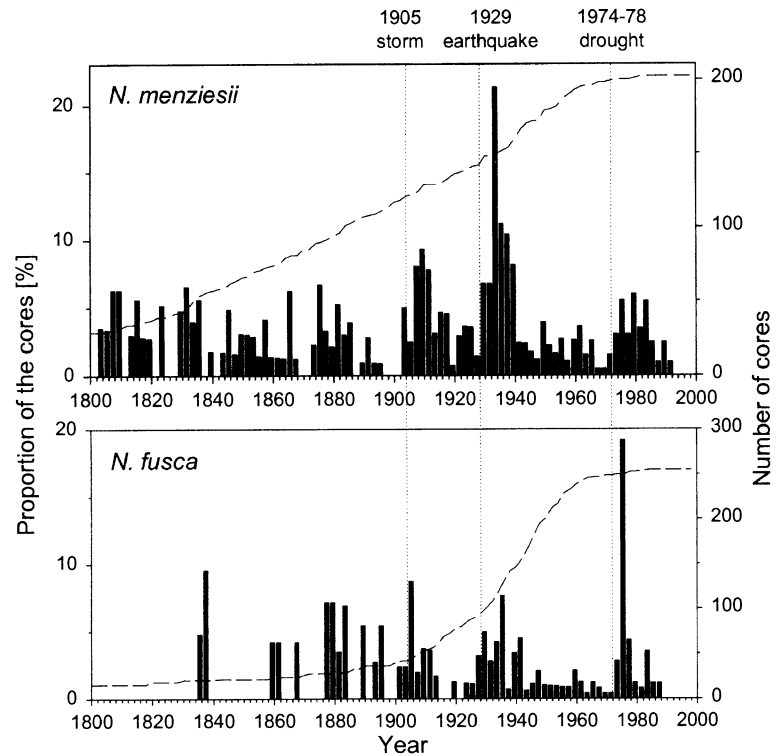


Fig. 1. Age-class distribution and canopy position of *Nothofagus fusca* and *N. menziesii* in six stands in the Matiri Valley (can. = canopy; subcan. = subcanopy; underst. = understory). The vertical point lines indicate the 1905 storm and the 1929 earthquake.



**Fig. 2.** Proportion of cores showing a growth release for five stands in the Matiri Valley (all the stands except the alluvial fan). The dashed lines show the number of cores available, and the vertical point lines indicate known disturbance events.

(Table 1c), with a high proportion (43-100 %) in the alluvial terrace, alluvial fan and rock slide, and a lower proportion (12-32 %) in the boulder field, steep side slope and gentle side slope stands. In these last two stands, there were young *N. fusca* in the canopy but most had established before 1929, with trees established after 1929 confined mostly to the subcanopy and understorey.

*Growth release*

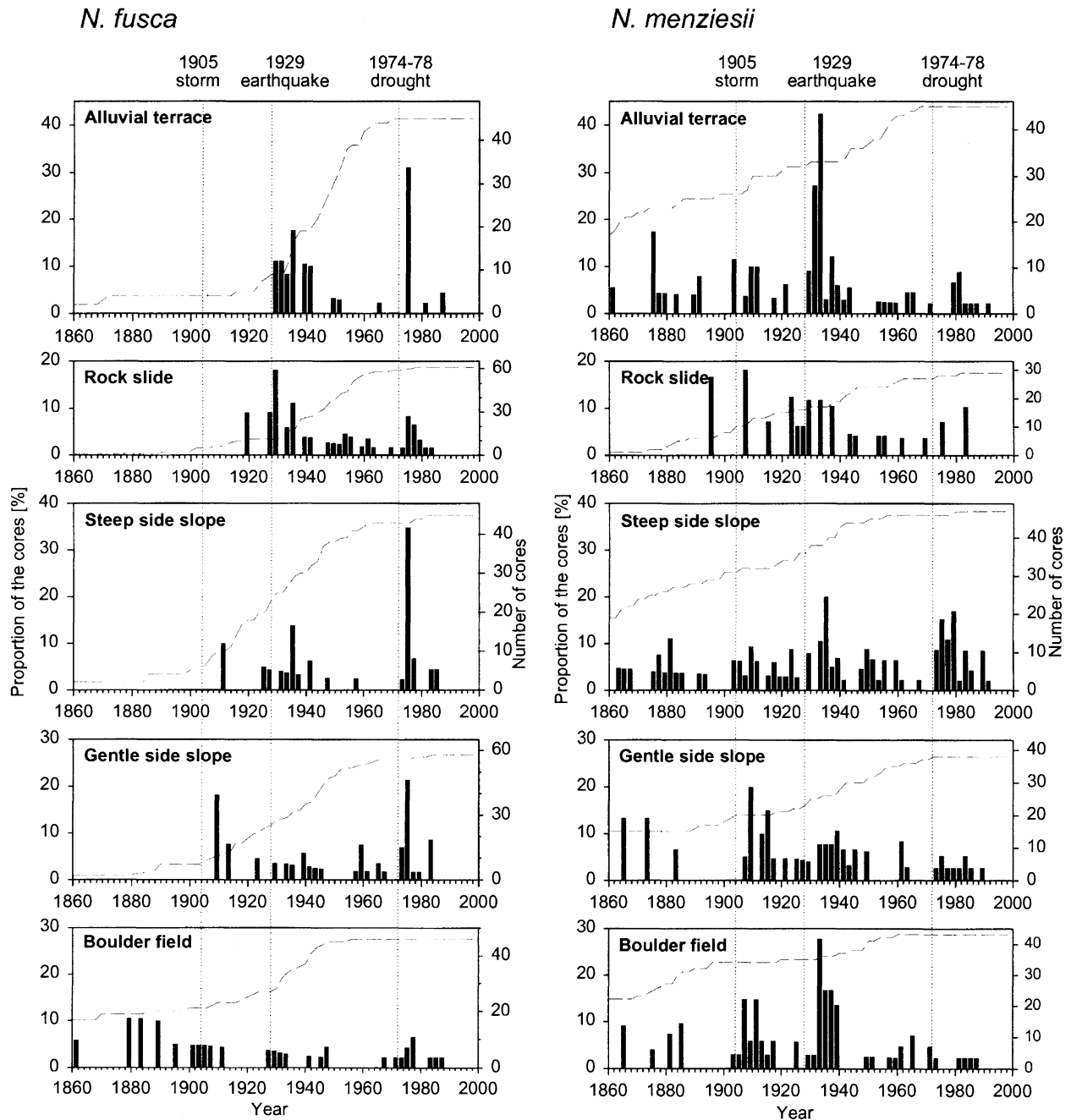
Three main periods of growth releases were visible during the 20th century (Fig. 2). The first two periods of

releases coincide with the upsurge in establishment of *N. fusca* in the first half of the century (Fig. 1). The earliest started around 1904-1905 and reached a maximum in 1908-1912. This period of releases coincides with two windstorms recorded as striking the region in 1898 and 1905 (Foster 1931; Benn 1990). Growth releases at the same time (1905-1912) have been recorded at different locations within 60 to 85 km of the study area (Stewart et al. 1991; Urlich 2000; Cullen pers. comm.).

The second period of releases started in 1929 and peaked in 1934-1936. It was particularly evident in *N.*

**Table 1.** Changes in the structure of six *Nothofagus* stands and in the growth of the trees following the Murchison Earthquake (1929) in the Matiri Valley. (a) Proportion of trees (all tiers) younger than 1929; (b) Proportion of *Nothofagus* having a growth release between 1929 and 1946; (c) Number of trees acceding to the canopy after a growth release in 1929-46 or growing directly from a newly established seedling (proportion of the canopy trees in 1999). Values in columns followed by the same letter are not significantly different utilising a *t*-test at *p* = 0.05.

Stands	a. Proportion of trees younger [%]		b. Proportion of trees with a release [%]		c. Number of trees acceding to the canopy	
	<i>N. fusca</i>	<i>N. menziesii</i>	<i>N. fusca</i>	<i>N. menziesii</i>	<i>N. fusca</i>	<i>N. menziesii</i>
<b>Landslide damaged stands</b>						
Alluvial fan	100 <sup>a</sup>	100 <sup>a</sup>	-	-	24 (100%)	0 (0%)
Alluvial terrace	61 <sup>bc</sup>	20 <sup>b</sup>	67 <sup>b</sup>	80 <sup>a</sup>	12 (71%)	7 (54%)
Rock slide	67 <sup>c</sup>	27 <sup>b</sup>	45 <sup>b</sup>	64 <sup>a</sup>	11 (48%)	4 (33%)
<b>Stable stands</b>						
Steep side slope	36 <sup>b</sup>	11 <sup>b</sup>	50 <sup>b</sup>	56 <sup>a</sup>	4 (31%)	6 (33%)
Gentle side slope	42 <sup>bc</sup>	32 <sup>b</sup>	33 <sup>ab</sup>	85 <sup>a</sup>	2 (18%)	2 (20%)
Boulder field	31 <sup>b</sup>	8 <sup>b</sup>	11 <sup>a</sup>	73 <sup>a</sup>	2 (13%)	1 (11%)



**Fig. 3.** Proportion of cores of *Nothofagus fusca* (left) and *N. menziesii* (right) showing a growth release for five stands in the Matiri Valley. The dashed lines show the number of cores available, and the vertical point lines indicate known disturbance events (results are given only when the number of cores is  $\geq 5$ ).

*menziesii*, with fewer releases in *N. fusca* (Table 1b). The growth disruptions immediately after 1929 are the most significant of the 19th and 20th centuries and are almost certainly a response to the 1929 earthquake. There is a sustained period of growth releases that continues for at least 15 years after the earthquake.

The most recent peak in growth releases is particularly evident in *N. fusca*, centred in 1975-1976, with a

slightly later peak in *N. menziesii*. These releases are most likely a response to a major drought in 1974-1978, following which there was widespread mortality of *N. fusca* in the nearby Maruia Valley (Hosking & Kershaw 1985).

There are insufficient data to compare the growth response of stands during the 1904-1905 release event (which was most likely a response to the 1905 storm). There are, however, some clear differences among stands

and species in their responses to the 1929 earthquake and the 1974-1978 drought (Fig. 3). Following the earthquake, a greater proportion of *N. menziesii* shows a growth release compared to *N. fusca*. Trees on the alluvial terrace reacted particularly strongly and quickly to the 1929 earthquake, while trees on the gentle side slope showed a low and late peak of releases, although the proportion of *N. menziesii* with a growth release is high (Table 1b). Tree responses to the drought differ clearly from the other disturbances with a short, sharp period of releases of *N. fusca* in 1975-1976, and later, more staggered, growth releases of *N. menziesii*. The steep side slope was the most affected by this last disturbance.

Although two major earthquakes struck the region, it appears that only the first had any detectable impact on the forests. The 1968 Inangahua earthquake, smaller and farther away, left no visible signs in the sampled stands. The following years (1968-1973) were often free of growth releases and any possible late response would be masked by the drought of 1974-1978.

Three other parameters were recorded on the cores: abrupt suppressions, the presence of tension wood and the eccentricity of growth. None gave interesting results, with the responses evenly distributed through time or forming slight peaks simultaneously with the releases.

#### Soil descriptions

In three stands (alluvial fan, alluvial terrace and rock slide), the soil pits revealed recently deposited material covering an older soil surface. On the alluvial fan there was a shallow (< 10 cm) and gravelly-sandy soil overlaying stones and gravel. This recent material had been deposited by the adjacent lateral creek. The alluvial terrace was likewise partly covered by 20 - 30 cm of recently deposited sand and gravel from a lateral creek, while the rock slide comprised 10 - 30 cm depth of stones overlying a deep (ca. 1 m), well-drained soil. The remaining three stands showed no evidence of recent deposition. The steep and gentle side slope stands both had deep, well drained soils, while soils in the boulder field stand varied from shallow on top of boulders to deep and gleyed in the hollows between boulders.

## Discussion

#### Earthquake response

The six stands varied in their response to the 1929 earthquake, which was the most significant disturbance impacting forests of the Matiri Valley in the 20th century. The nature of the response depended on whether or not a stand was affected by soil deposition presumably

triggered by the earthquake. In three stands, material deposited by water or mass movement had destroyed all (alluvial fan) or part (alluvial terrace and rock slide) of the original forest, forming large gaps in the forest canopy. All three of these landslide damaged stands show a major pulse of *N. fusca* establishment after the 1929 earthquake, with 63 - 77 % of trees already in the canopy (Fig. 1), suggesting that gaps were too large to be closed by lateral crown growth or by surviving small trees. In the alluvial fan, seedlings colonized the new ground, and the canopy is now an even-aged stand of *N. fusca*, with *N. menziesii* restricted to the understorey (Fig. 1). In the alluvial terrace and rock slide, *N. fusca* also dominated regeneration in the large gaps, growing among surviving trees of both *Nothofagus* species. Even-aged stands of *N. fusca* developing after large disturbances in mixed *Nothofagus* forest have been observed previously in New Zealand (e.g. Foster 1931; Moorhouse 1939). Both species colonize new surfaces at the same time, but the faster growing *N. fusca* quickly overtops *N. menziesii*. Studies in other *Nothofagus* forests have shown that landslides (from rapid soil slides to isolated rock falls) can cause 74 % of the mortality and 45 % of the damage sustained during an earthquake (Allen et al. 1999), and that the highest levels of damage occur on unstable surfaces (Kitzberger et al. 1995).

Landslides were, however, not the only cause of tree mortality during the earthquake: the presence of releases in 1929 and 1930 in the three stands not subject to landsliding shows that trees must have died directly from shaking. The 1929 earthquake was strong enough to kill trees on flat ground up to 70 km from the epicentre – releases in 1929 were observed in *N. fusca* by Stewart et al. (1991) and in *N. menziesii* by Urlich (2000) – and to damage trees farther away, with tree falls observed up to 120 km and broken branches up to 250 km from the epicentre (Benn 1992). Allen et al. (1999) likewise observed mortality due to tree falls farther from the epicentre than due to rock slides.

Compared to the stands affected by landsliding, the stands on stable surfaces had a lower rate of tree establishment following the earthquake (particularly for *N. fusca*), with fewer of those trees having reached the canopy, but a comparable number of growth releases (Figs. 1, 3; Table 1). This suggests that only small gaps were created in these stands during and after the earthquake. Opening of the canopy initiated regeneration and release, but the gaps were primarily closed by lateral crown growth and by the growth of surviving subcanopy trees. In contrast to the large gaps formed by landslides, which were dominated by *N. fusca* regeneration, in small gaps *N. menziesii* and *N. fusca* trees acceded to the canopy in roughly equal proportions (Table 1c), supporting previous observations by Stewart & Rose (1990)

and Runkle et al. (1997) that both species have a similar chance of reaching the canopy in small gaps.

All of the stands, except that on the gentle side slope, have a higher proportion of *N. menziesii* among trees that established prior to 1929, while *N. fusca* dominates establishment after 1929 (Fig. 1; Table 1a). This age structure suggests that (1) *N. fusca* was previously less common in these stands and that the damage associated with the 1929 earthquake has resulted in a shift in canopy composition towards a higher proportion of *N. fusca*, or, (2) that *N. fusca* suffered higher mortality than *N. menziesii* following the earthquake. A shift in canopy composition cannot be excluded, but we observed numerous *N. fusca* logs on the ground suggesting that *N. fusca* was previously common and that mortality of this species following the earthquake was high. The two species therefore show a markedly different response to the earthquake, in line with previous observations of their regeneration behaviour (Ogden 1988; Stewart & Rose 1990): *N. fusca* probably suffered higher mortality during the event but dominated canopy recruitment in the large gaps formed by landslides, as well as recruiting into smaller canopy gaps; *N. menziesii* better survived the event but canopy recruitment of this species was confined to small gaps and resulted primarily from the release of surviving understorey and subcanopy trees (Fig. 1). Overall, our results show that a single large earthquake can have highly variable impacts across the landscape and that subsequent forest recovery is broadly predictable from the type of damage suffered.

Landsliding and shaking killed trees during the 1929 earthquake, but the period of releases following the earthquake is too long to be related only to direct damage, and other causes must have killed trees more than 15 yr after the event (Fig. 3). Long periods of dieback are well documented for New Zealand *Nothofagus* forests following major disturbance (e.g. Skipworth 1983; Hosking & Kershaw 1985; Hosking & Hutcheson 1986, 1998). The main cause is generally an increase in pathogens, especially insects and fungi, with disturbance predisposing stands to attack by weakening the trees and increasing the availability of dead wood (Wardle 1984). Rawlings (1953) reported the most severe outbreak of *Nascioides enysii* (*Buprestidae*) in the Murchison area after the 1929 earthquake, but Milligan (1972) stated that this insect is not able to directly kill trees. The fungus *Sporothrix*, dispersed by the *Platypus* beetle, is often responsible for dieback in *Nothofagus* forest (Milligan 1972; Faulds 1977; Hosking & Hutcheson 1998), but no historic account confirms the hypothesis of a *Platypus* attack after 1929. However, the delay of 4–5 yr before the increase in mortality, such as seen on the gentle side slope (Fig. 3), and its culmination 5–8 yr after the earthquake (between 1933 and 1936) is consist-

ent with the mortality pattern observed by Hosking & Hutcheson (1998) for *Sporothrix* induced dieback following a windstorm.

The 1929 earthquake was perhaps not the only event affecting trees in this period. Several dry years were recorded around 1930 (Anon. 1984a and unpubl. data), which may have contributed to a weakening of the trees. Kitzberger et al. (1995) found in Argentina a higher rate of mortality after an earthquake which occurred in combination with a drought, than after other earthquakes. The respective roles of the earthquake and the drought are not known, but the different patterns of release following the 1929 earthquake and the 1974–1978 drought (Fig. 3 and see below) suggest that drought was not a major cause of tree death.

#### *Earthquakes and other disturbances*

Our results suggest that three major disturbances affected forests of the Matiri Valley during the 20th century: a storm in 1905, an earthquake in 1929 and a drought between 1974–1978. Each disturbance resulted in a different pattern of damage and forest recovery. The regeneration response of *N. fusca* suggests that the storm caused the greatest damage to the gentle and steep side slopes (Fig. 1), presumably the most exposed sites, but its impact in other stands may have been obliterated by the earthquake. The long period of growth releases after the storm suggests dieback in the following years. Without historical data, it appears impossible to recognize the storm from the earthquake impacts. Both resulted in similar long periods of releases, starting shortly after the event but typically peaking later (Fig. 3). After earthquakes, Jacoby et al. (1988), Kitzberger et al. (1995) and Wells et al. (1999) observed major growth suppressions in tree-rings, followed by slow recoveries. Although this pattern is not specific to earthquakes, it could be a useful distinguishing feature, particularly when associated with tension wood (e.g. LaMarche & Wallace 1972; Wiles et al. 1996). In the Matiri Valley, however, only one sampled tree showed a growth suppression around 1929. The dieback that followed the storm and the earthquake may have killed many of the trees damaged directly by the disturbance, leaving only information about the less damaged trees. It appears that tree-ring data alone are inadequate to distinguish earthquake from other disturbance impacts in New Zealand *Nothofagus* forests.

The drought, in contrast, resulted in a different growth release pattern, with a sharp peak of *N. fusca* releases in 1975–1976, due mostly to young trees in the understorey (Vittoz et al. in prep.). Growth release was also most pronounced in the steep side slope stand, which was probably the driest site. Other studies are necessary to



verify if this is a typical pattern associated with droughts in *Nothofagus* forest, or if the numerous young *N. fusca* that established after the earthquake, and were common in the understorey of most stands, were at least partly responsible for the large number of growth releases in this species.

Veblen & Ashton (1978) in Chile, Kitzberger et al. (1995) in Argentina, and Wells et al. (1999) along the Alpine Fault in New Zealand have shown that earthquakes can be the dominant factor driving the dynamics of forests in tectonically active regions. We show that earthquake impacts can vary considerably within a local area resulting in heterogeneity in the patterns of forest recovery and leading to stands of differing structure and composition. Like other disturbances (Stewart et al. 1991), this variability in earthquake impacts creates a range of regeneration opportunities, permitting the coexistence of canopy species in mixed *Nothofagus* forests.

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