Microclimate gradients across a forest edge

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Abstract: Despite the importance of forest edges in ecology, only one study has previously been carried out in New Zealand on the modification of climate across forest edges. We measured light exposure, wind speed, air and soil temperature, and vapour pressure deficit (VPD) perpendicular to a north-south aligned, mature, edge of native broadleaf rainforest adjoining grazed pasture. At a point 80 m into the forest from the edge, light was only c. 0.7% and wind speed c. 20% of that in the open, and there was much less diurnal fluctuation in soil temperature, air temperature and VPD. The gradient of microclimate near the edge, as measured with a third (mobile) weather station, was abrupt for soil temperature and similar to the pattern of light exposure, with almost complete change over about 10 m. The gradient was less steep for wind speed, air temperature and VPD, with at least 40 m being required to stabilise these variables when wind was directed into the forest. These findings suggest that forest buffers of at least 40 m may be needed to protect forest reserves and streams from climatic exposure.

Keywords: Microclimate; sunlight; wind; temperature; moisture; riparian; edge effects; forest remnants; temperate rainforest.

Introduction

Extensive fragmentation of the once extensive tracts of contiguous native forest has occurred in New Zealand over the past 150 years (Ministry for the Environment, 1997). Clearance of forest may profoundly influence ecosystems by exposure to sunlight and wind and the consequent stresses of temperature fluctuation and desiccation. Forest fragmentation has created large areas subject to "edge effects" in which ecological conditions contrast with interior forest as regards vegetation structure and productivity, under-storey species, and microclimate (Forman, 1995; Murcia, 1995; Matlack and Litvaitis, 1999).

Microclimate can be defined as the climate at small scale, say from 0.01 to 1000 m (Oke, 1978). There are at least five variables which, together characterise the microclimate: sunlight exposure, wind exposure (magnitude and direction), precipitation, temperature (of air and soil), and moisture content (of air and soil). Microclimate conditions strongly influence ecosystem processes (Whittaker, 1975), and changes in microclimate of the magnitude that can occur near forest edges may dramatically alter ecosystem structure and function (Murcia, 1995; Matlack and Litvaitis, 1999).

The microclimate across forest edges has been the subject of a number of studies internationally, perhaps the most comprehensive being those of Chen and co-workers (Chen *et al.*, 1993; 1995) in the Pacific North West of the USA. However, to date only one study has been made in New Zealand's native rainforests, which are characterised by high species richness and low light levels (McDonald and Norton, 1992), in contrast to most temperate forests (Dawson and Sneddon, 1969). Young and Mitchell (1994) reported on light, air temperature and moisture gradients, and vegetation patterns in native podocarp-broadleaf forest fragments in Northland. They found that the influence of open country on moisture and temperature extended up to 50 m into the forest from the forest edge.

Our interest in microclimatic gradients near forest edges, is driven primarily by concern with microclimatic exposure of stream riparian zones. The microclimate of riparian zones influences stream ecology by affecting habitat for terrestrial life stages of aquatic or semi-aquatic animals, including birds and aquatic insects (Jackson and Resh, 1989), as well as by controlling stream light exposure and water temperature (Rutherford *et al.*, 1997).

In this paper we characterise microclimate in native forest *versus* pasture and report measurements

of microclimate gradients perpendicular to a mature forest edge. We deliberately chose a mature edge for study because the extent of edge influence and patterns of influence can change with time since edge creation as vegetation near the edge responds, particularly, to increased light exposure (Matlack and Litvaitis, 1999). As well as being of interest for terrestrial ecologists concerned with the habitat of forest remnants, our observations have implications for the width of riparian buffers needed to protect stream ecology.

Methods

Study area

The study site is in gently sloping terrain (c. 4°), at 440 m altitude at the edge of Pirongia Forest Park (38°03'S, 175°04'E, Kawhia Ecological District). The forest is native broadleaf rainforest, with tawa *(Beilschmiedia tawa* (A. Cunn.) Benth. et Hook.f.) dominating the canopy (height c. 20 m). Feral goats and pigs are responsible for an impoverished shrub layer and ground disturbance. A timber mill (the Te Rau-a-moa mill) operated in the area until the 1930's (Peter de Lange, Department of Conservation, Auckland, N.Z., *pers. comm.*), which probably explains the local absence of tall podocarp trees in this "easy" (for log handling) terrain. Apparently a fire swept through the area about 100 years ago, which may be responsible for the absence of northern rata (*Metrosideros robusta* A. Cunn.). The forest was cleared to near the present edge for farming about 90 years ago (Suzanne Paalvaast, land owner, Waipa District, N.Z., *pers. comm.*).

The forest edge is almost straight, aligned almost north-south (20°) for 800 m, and delineated by a livestock fence. We were not able to obtain a precise history of the edge, but there may have been livestock ingress from the adjacent pasture between the times of forest clearance and fencing, possibly in the 1940's or 1950's. Close to the edge the forest differs from the interior in species composition and foliage density. There seems to have been some "infilling" of gaps between the original edge and the fenceline with early successional species, as well as an overall adjustment of vegetation to increased light and climatic exposure.

Canopy trees in the interior forest have the following relative abundance ranking: *B. tawa* (tawa) >> *Elaeocarpus dentatus* (J.R. et G. Forst.) Vahl (hinau) > *Weinmannia racemosa* Linn.f. (kamahi) ~ *Litsea calicaris* (A. Cunn.) Benth. et Hook.f. (mangaeo) ~ *Laurelia novae-zelandiae* A. Cunn. (pukatea). The understorey plants have the following relative abundance ranking: *Melicytus ramiflorus* J.R. et G. Forst. (mahoe) > *Cyathea smithii* Hook. f. (Smith's tree fern) > *B. tawa* (tawa saplings) > *Dicksonia squarrosa*

(Forst. f.) Swartz (wheki tree fern). *Freycinettia banksii* A. Cunn. (kiekie) is a prominent climber and there is abundant *Ripogonium scandens* J.R. et G. Forst. (supplejack) and some rata (*Metrosideros* spp.).

Within 5 m of the forest edge, relative abundance ranking of plants is: *D. squarrosa* > *C. smithii* > *M. ramiflorus* > *E. dentatus* ~ *Knightia excelsa* R.Br. (rewarewa). *Coprosma grandifolia* Hook.f., *Pseudopanax crassifolius* (A. Cunn.) C. Koch (lancewood), and a few large (apparently residual) *B. tawa* are also present. One *Prumnopitys ferruginea* (D. Don) Laubenf. (miro) specimen was recorded. Abundant growths of *Metrosideros diffusa* (Forst.f.) Smith (rata) and *Rubus cissoides* A. Cunn. (lawyer), which were seldom found in the interior except in old treefall gaps, contribute to a comparatively high foliage density and partially "seal" the edge.

Approach

In order to characterise the microclimate in forest compared to nearby open pasture, two weather stations were located at each end of a 160 m transect, perpendicular to, and bisected by, the forest edge. Based on previous studies (Young and Mitchell, 1994) and pilot work (Baas and Mennen, 1996) we expected that locations 80 m from the forest edge would be beyond edge effects on microclimate. Data from the two fixed weather stations were summarised for two 24 day periods to indicate average diurnal patterns in late winter (10 August to 4 September, 1996) and late summer (12 February to 8 March, 1997).

The pilot work suggested that temperature and moisture conditions are typically steady in the early afternoon, and contrasts between forest and pasture conditions are most marked at this time of day. Therefore, spatial gradients in microclimate along the transect were recorded during the early afternoon (between 12:00 and 15:00 hours NZST) on days of contrasting weather. We used a third weather station, referred to as the "transect station", to measure microclimate variables at points marked by pegs on a logarithmic progression: 5, 10, 20, 40 and 80 m from the forest edge in both directions.

Instrumentation and data analysis

The weather stations were each equipped with sensors for light, air movement, air temperature and relative humidity, and soil temperature. Photosynthetically available radiation (PAR) was measured with LI-192SA sensors (LI-COR Inc. Lincoln, Nebraska, USA). Wind speed was measured with cup anemometers, and wind direction with wind vanes, positioned 2 meters above the ground. A Vector Instruments A101M sensor pair (Vector Instruments, Denbighshire, North Wales, UK)

was used for the forest station and a Maximum type 40 sensor pair (NRG Systems, Hinesburg, VT, USA) for the pasture station. Combined air temperature-relative humidity sensors (Vaisala Humitter 50Y, Vaisala Oyj, Vantaa, Finland) were fitted in radiation shields located 1.5 meters above ground. Soil temperature was measured with thermistor probes (LI-1000-15, LI-COR Inc.) inserted 100 mm into the soil with their cables covered with aluminium foil to prevent solar heating.

Inter-calibrations were made for the various sensors by running the weather stations side-by-side for several days prior to, and immediately after, each field deployment. Data were logged with Campbell CR10 data loggers (Campbell Scientific, Logan, UT, USA) which were routinely programmed for 5 min averaging of readings made every 5 s. Relative humidity data were used, together with air temperatures, to calculate vapour pressure deficit (VPD, an index of the drying capacity of air) using the formula of Lowe (1976) for the saturation vapour pressure. We report non-parametric statistics (Iman and Conover, 1983) for long-term summaries, because the microclimate data for some variables have appreciably skewed distributions.

Transect measurements

During measurements made along the transect, all three weather stations logged 1 min averages of data recorded every 5 s. The transect (mobile) weather station was positioned for at least 7 min sequentially at each point on the transect in turn, and the final 5 min of the record was analysed. These 5 min of data were matched with data obtained simultaneously at the forest and pasture weather stations so that the spatial patterns that we wished to define could be distinguished from temporal changes in weather.

Characterisation of light climate and vegetation

The visible light exposure along the transect was measured using a pair of LAI-2000 Plant Canopy Analysers (LiCor Inc., Lincoln, Nebraska). These instruments, based on fish-eye optics, simplify characterisation of light climates by obviating the need to deploy radiation sensors for extended periods (Davies-Colley and Payne, 1997). One of the canopy analysers was used to log incident light distributions in the open, while the other was used to take readings along the transect. Five measurements were taken 0.5 m above the ground at each of 11 pegs along the transect. The canopy analyser data were used to calculate Diffuse-non-interceptance (DIFN, LI-COR, 1991), an estimate of the lighting under a canopy as a proportion of that incident under a perfectly uniform sky, and a

useful index of the time-averaged light exposure (Davies-Colley and Payne, 1997).

Plant stem density and basal area of all plants > 30 mm DBH was measured in 10 m x 10 m quadrats centred on each of the five pegs in forest and in three 5 m x 10 m rectangles along the forest edge. Plants were identified as part of these surveys so as to provide an indication of relative abundance. Visualisation of the forest shade and the floristic composition was aided by photography with a fish-eye lens (Minolta 7.5 mm f/4 MD lens, 180 degree field of view).

Results

Lighting and vegetation patterns

Stem density of forest plants is appreciably higher, and basal area slightly higher, near the edge than elsewhere along the transect in forest (Fig. 1a, b). Light exposure,
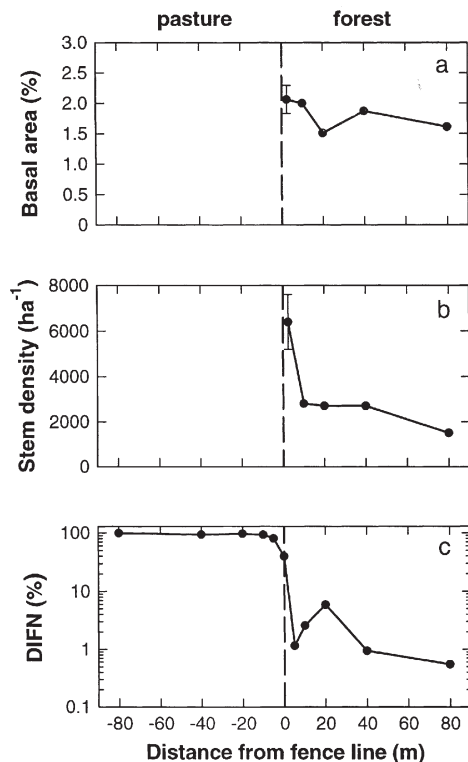

Figure 1. Vegetation parameters and light exposure along the 160 m transect from open pasture to forest interior, perpendicular to the forest edge. (a) basal area and (b) stem density of trees and shrubs calculated from survey of DBH. (c) DIFN values calculated from canopy analyser measurements. Mean and standard error bars are given in panels (a) and (b) near the edge where three replicate vegetation plots were surveyed.
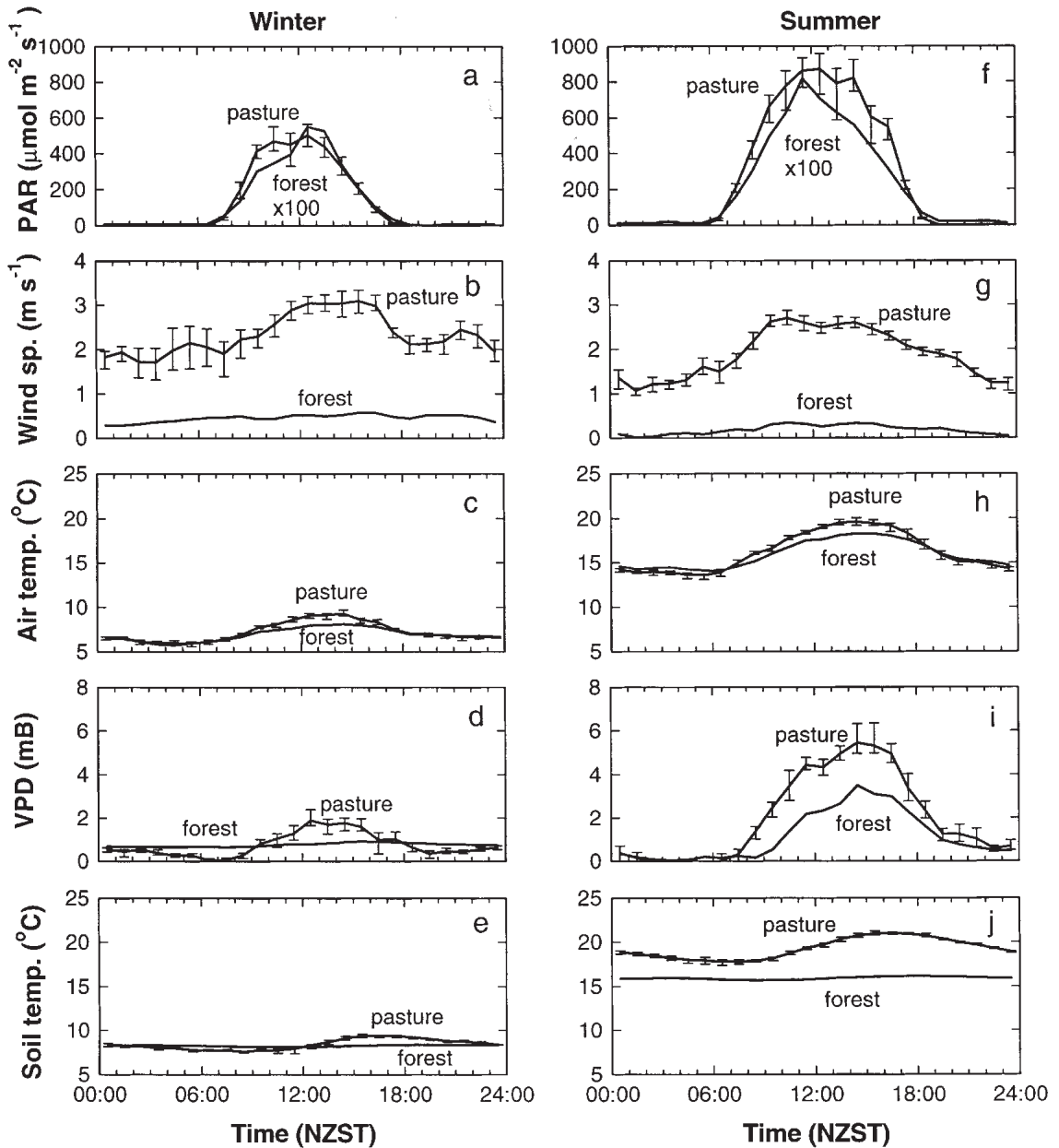
Figure 2. Diurnal patterns of microclimate variables in pasture and in forest measured over 24 days in late winter (10 August to 4 September, 1996), and late summer (12 February to 8 March, 1997). Medians are plotted with bars indicating 95% confidence intervals (calculated after Iman and Conover, 1983) on the pasture data (CI intervals were generally smaller for the forest data). Note the scale change between forest and pasture for PAR.

as indicated by canopy analyser readings (Fig 1c), is generally low in the forest (ranging from 0.5-6% of incident). At 20 m into the forest a peak in lighting occurs near a canopy gap caused by the fall of a large *B. tawa* tree. The low light exposure at 5 m from the edge is apparently related to the high density of foliage within 5 m of the edge, which compensates for the generally smaller size of plants compared with the interior.

Microclimate contrast: forest *versus* pasture

In both winter and summer, much less light reached the forest floor than was received in pasture (Fig. 2a, f). In summer, the average daily PAR in forest was 0.20 mol m^{-2}, about 0.76% of the 26 mol m^{-2} average daily PAR incident at the pasture station. In winter, the average daily PAR was 0.086 mol m^{-2} in forest, about 0.75% of the 12 mol m^{-2} incident. These light exposure values are somewhat higher than indicated by canopy analyser measurements (DIFN = 0.55%). The lack of symmetry of the average forest lighting reflects the distribution of canopy gaps at the forest station.

Wind speed was consistently higher in pasture than in forest (Fig. 2b, g). The ratio of wind in forest to that in pasture (Mean ± SE) averaged 20 ± 3% in winter and 10 ± 3% in summer. Even though the instantaneous wind was highly variable, the wind averaged over hourly intervals tended to follow the same diurnal pattern in forest as in pasture. Wind tended to be strongest during daylight hours, peaking between noon and late afternoon (12:00-17:00 NZST) in winter, and before noon (10:00-12:00 NZST) in summer.

Air temperature in forest followed a similar diurnal pattern to that in pasture (approximately sinusoidal), although temperature was consistently higher in pasture than in forest during daylight for both winter and summer (Fig. 2c, h). Air temperature maxima in pasture and forest were generally reached at about the same time (c.14:30 hours NZST) in both seasons.

The diurnal pattern of VPD (Fig. 2d, i) was more marked in summer than in winter and more marked in pasture than in forest. VPD maxima occurred between 14:00 and 15:00 NZST. At the forest site, VPD was fairly constant over the day during the winter period, whereas in summer the VPD in the forest displayed a similar day-time pattern to pasture, although the peak was shorter and lower.

Soil temperature at 100 mm depth was about 10 °C higher in summer than in winter (Fig. 1e, j). Soil temperature in forest displayed little diurnal variation in either season. In contrast, pasture soil temperature varied diurnally in a smooth, skewed sinusoidal pattern, with minima near dawn and maxima in the afternoon between 16:00-17:00 hours NZST. Soil temperature lagged behind air temperature by about 1-2 hours at the pasture site.

Although Fig. 2 shows general microclimate features, particularly typical diurnal patterns, some interesting details are obscured. On sunny days the PAR in the forest was highly irregular and changeable by comparison with the smooth and symmetrical pattern in the open. When the sun's disc was aligned with gaps in the forest canopy, "sunflecks" (Chazdon and Pearcy, 1991) caused sharp spikes of light (up to 85 micro-mol photons m^{-2}s^{-1}) on an otherwise low record of PAR in deep shade (c. 3 micro-mol photons m^{-2}s^{-1}). On cloudy days with diffuse lighting, the PAR in the forest closely followed the pattern at the pasture site, showing that the forest PAR was a nearly constant proportion of diffuse incident PAR (c. 0.7%).

On windy days, forest wind speed followed the wind record in pasture fairly closely [e.g., forest wind speed (mean ± SE) as a proportion of pasture wind speed = 24 ± 6% on a windy, overcast day, 1 March, 1997]. However, on calmer days the air movement in forest was a smaller proportion of, and less strongly related to, that in the open [e.g., proportion of pasture wind speed (mean ± SE) = 13 ± 14% on 13 March, 1997, a nearly calm day].

There was little diurnal fluctuation in air temperature, VPD or soil temperature on cloudy days, and the forest records for these variables were very similar to those for pasture. However, on sunny days, all three variables showed appreciable diurnal variation in pasture attributable to heating during daylight hours. These differences between pasture and forest temperature and VPD imply a gradient of conditions perpendicular to the forest edge.

Microclimate gradients across the forest edge

Figure 3 shows wind speed, air temperature, VPD and soil temperature recorded along the transect on a sunny day with a light breeze directed from the north almost parallel with the forest edge. Simultaneous measurements at the forest and pasture weather stations are also plotted (*versus* location of the weather station on the transect) so that temporal changes in weather can be distinguished from the changes with distance (i.e., spatial gradients) that we wish to characterise. This is particularly important for wind speed, which is variable over time. For example, wind speed in pasture changed appreciably during the transect measurements (Fig. 3a).

To aid the interpretation of wind exposure along the transect, the transect measurements were divided by the simultaneously measured wind speed at the pasture station. The resulting wind speed relative to that in pasture (expressed as a percentage) provides a *wind exposure index* (Fig 3b). The wind exposure generally decreased along the transect in pasture approaching the forest, with the steepest decline
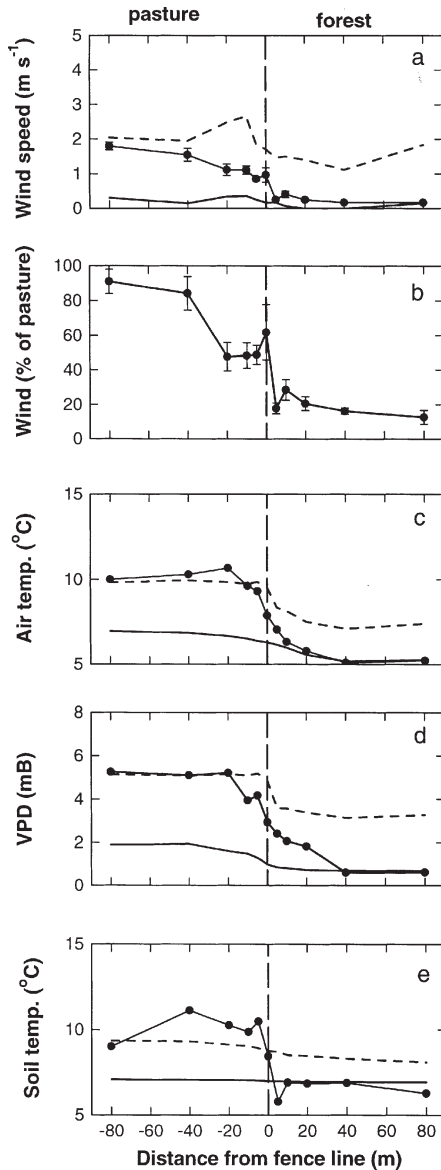
Figure 3. Profiles of microclimate variables measured along the 160 m transect. Data are for 25 August, 1996, a sunny, fairly calm, day with a northerly breeze (aligned with the edge). Each panel shows the measurements recorded at the pasture station (dashed line) and at the forest station (continuous line) simultaneously with the data actually recorded at points on the transect (bold line with solid dots). The standard errors calculated for five sets of 1 min averages are given as bars on the wind data (other variables were less intrinsically changeable). Wind data is given both as recorded wind speeds for the three stations (Panel a) and as wind speed on the transect as a percentage of pasture wind speed, an index of wind exposure (Panel b).

occurring near the fence line. Wind speed measured in the forest on this occasion was generally similar to that at the forest station except close to the forest edge (Fig. 3a). An unexpected oscillation in wind exposure occurred near the edge (Fig. 3b). The peak at the edge itself may be merely a statistical fluctuation on consideration of the standard error bar, but the trough at 5 m into the forest probably reflects the high foliage density at this point, with correspondingly low light exposure (Fig. 1c).

Associated with the change in wind speed during the transect measurements was a decline in air temperature and VPD (Fig. 3c, d). Despite these temporal changes, gradients in both temperature and VPD can be discerned at the forest edge over a region about 40 m either side of the edge. Soil temperatures, in contrast, fell abruptly near the forest edge (Fig. 3e), in a pattern similar to that of sunlight exposure (Fig. 1c). The index of wind exposure obtained by normalising to wind speed in the open was also calculated for seven other sets of transect measurements (Fig. 4). Five sets of data obtained with the wind directed out of the forest (prevailing westerlies) are displayed separately (Fig. 4a-d) from data obtained on two occasions with (comparatively infrequent) easterly wind directed into the forest (Fig. 4e-h).

On days when wind was directed out of the forest, wind speeds measured along the transect dropped rapidly near the edge to levels characteristic of the interior forest (Fig. 4a). Downwind of the forest edge a "sheltering" effect of the forest extended ~ 40 m into pasture. On days with easterly winds directed into the forest (Fig. 4e), wind influences from pasture were observed to extend > 40 m into the forest. The wind exposure gradient was appreciably less steep on these days and apparently insensitive to the magnitude of wind speed. A trough of wind speed at 5 m occurs in all of the wind exposure profiles (Fig. 3b, 4a, e), showing this to be a consistent feature.

During most transect measurements, air temperature, VPD, and soil temperature were reasonably stable at the pasture and forest stations, in contrast to windspeed. Thus transect data alone serve to characterise spatial patterns in Fig. 4. Air temperature and VPD on the transect in pasture were generally similar to values measured at the pasture station until within 20 m of the forest edge. However, in the forest the apparent "edge effect" sometimes extended for > 40 m from the edge (notably for the 27 March, 1997, a sunny day with wind directed into the forest – Fig. 4f, g). On overcast days there was minimal contrast in air temperature between forest and pasture (for example, 29 August, 1996 and 11 March 1997). On some days (e.g., 11 February, 1997 and 24 March, 1997) a peak of air temperature and VPD occurred right at the edge. An abrupt change in soil temperature occurred at the forest edge on all
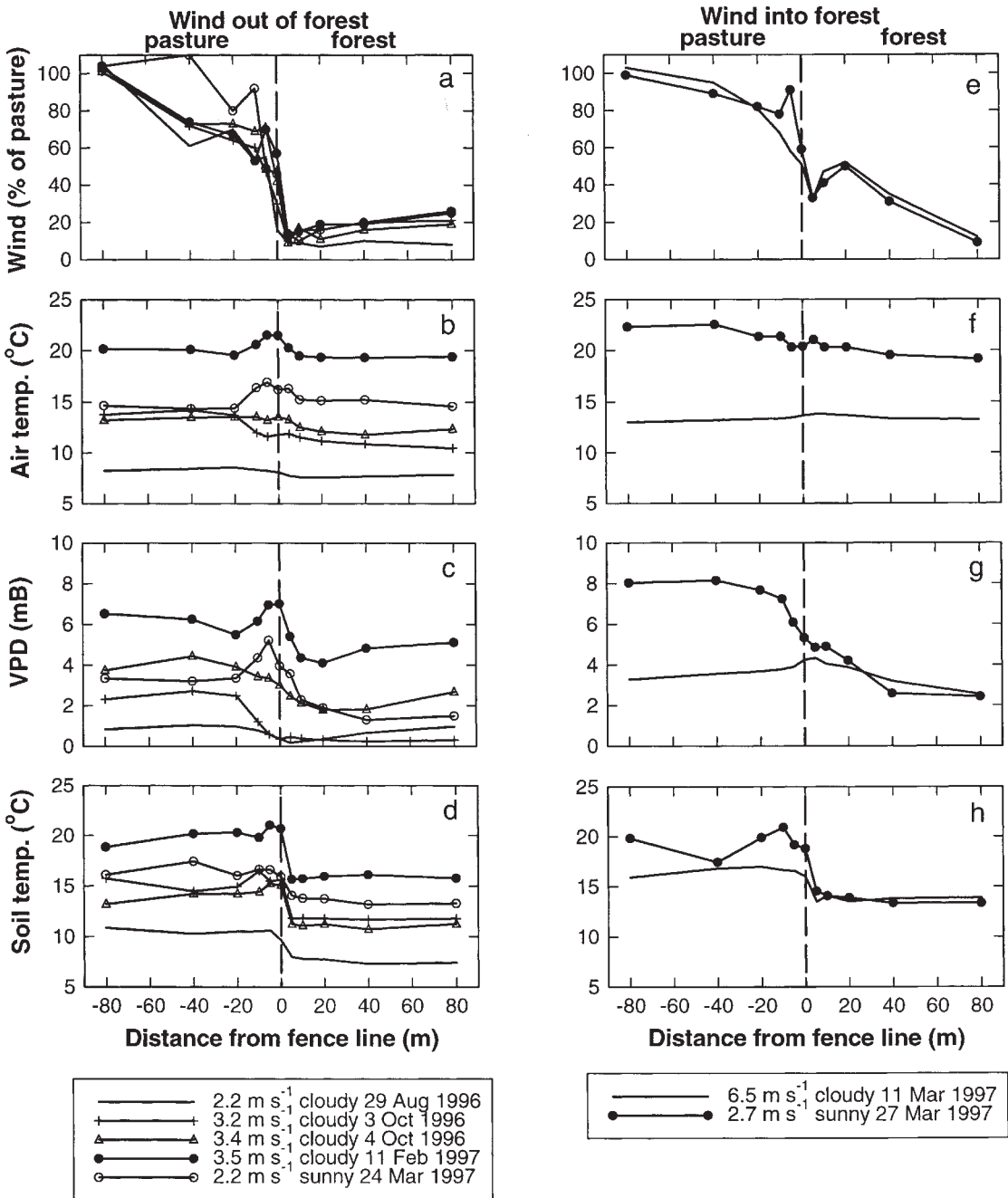
Figure 4. Microclimate profiles along the 160 m transect on five days with westerly (prevailing) winds directed out of the forest and on two days with easterly winds directed into the forest. Wind exposure along the transect is indicated by plots of the percentage of pasture wind speed. The key gives average wind speeds in pasture during the transect measurements and an indication of lighting conditions.

transects (Figs 4d, h). Forest conditions of soil temperature were generally reached within 5 m from the forest margin.

Discussion

Forest lighting and edge vegetation

We found the forest edge to have similar basal area to the interior forest, but appreciably higher stem density. There is also a higher species richness at the edge than in the interior, and a shift in composition towards high light "pioneer" plants similar to those found in treefall gaps in the interior. For example, *D. squarrosa* dominates the treeferns at the edge, cf. *C. smithii* the interior, and *K. excelsa* and *M. ramiflora*, are more abundant at the edge. Treefalls of *B. tawa* and dead *W. racemosa* specimens were noted near the edge. These findings are broadly consistent with those of Young and Mitchell (1994) who conducted comprehensive analyses of vegetation structure near native podocarp-broadleaf forest edges in Northland. They reported changed plant composition, higher plant biomass, greater species richness, and greater tree mortality at the edge by comparison with the interior.

Light exposure within the forest as indicated by the DIFN value varied along the experimental transect, apparently reflecting point-to-point variability in the forest canopy. Values of DIFN in the forest ranging from 0.55 to 6% are consistent with McDonald and Norton's (1992) measured PAR levels in the range 1.3-5.2% of incident for podocarp-broadleaf rainforest in Westland. New Zealand native rainforest is typically very shady and comparable in this and other respects to tropical rainforests in which light exposure < 1% of incident have been reported (Chazdon and Fetcher, 1984; Torquebiau, 1988; Canham *et al.*, 1990).

The instantaneous lighting in forest under clear sun can be very changeable, owing to the movement of sun flecks, whereas under diffuse incident lighting, the forest light closely follows the temporal pattern of incident lighting. This suggests that forest light exposure can be estimated reasonably accurately from instantaneous measurements with PAR sensors on fully overcast days (Davies-Colley and Payne, 1997). PAR in forest was somewhat higher than indicated by canopy analyser DIFN, probably reflecting the spectral composition of forest shade light. The canopy analyser is insensitive to green light transmitted through foliage owing to its 490 nm cut-off filter (LI-COR, 1991) and therefore tends to under-estimate total forest lighting.

The gradient of light exposure was very steep near the forest edge at our study site, with levels characteristic of interior forest reached within 5 m. The growth of plants near the edge in response to the high light exposure has tended to seal the edge, creating an "edge canopy" (Matlack and Litvaitis, 1999). Climbers, notably rata (*Metrosideros* spp.) and lawyer (*R. cissoides*), seem to be particularly important in the edge canopy formation. Mature edges, such as that we studied, may be expected to have steeper and more complex, microclimate gradients than freshly created edges (Kapos *et al.*, 1997; Matlack and Litvaitis, 1999).

Microclimate contrast, forest *versus* pasture

The near-floor environment of the forest is very much shadier, much less windy, and fluctuates less markedly through the day in temperature and moisture than in the open. The forest is cooler and moister during the day and, to a lesser extent, warmer and drier at night. In a general way these characteristics of the forest microclimate are well known and common to both coniferous and broad-leaved forest from the boreal zone to the tropics (e.g., Ghuman and Lal, 1987; Chen *et al.*, 1993).

We found that the wind exposure in the forest averaged about 20% of that in the open, and seemed to increase with wind strength. This finding is consistent with the work of Chen *et al.*, (1993) on air movement in Douglas fir forests of the Pacific North West of USA, and with the classic work of Raynor (1971) who found that wind in the interior of a pine plantation was about 20% of wind in the open. The air movement in the forest may be attributed to the penetration through the foliage of turbulent eddies induced by wind flow over the canopy (Lee, 1978).

We found that on sunny days, air temperature and VPD were diurnally more variable, and contrasted more markedly between forest and open land than on cloudy days, as has been reported by others (Ghuman and Lal, 1987; Chen *et al.*, 1993). On cloudy days there is little heating of soil and air, which explains the lack of diurnal fluctuation in both temperature and VPD. Soil temperature, like air temperature, fluctuated diurnally with greater amplitude in pasture than in the forest, although the peaks of soil temperature lag behind those of air temperature, because of the time taken for conduction of heat from the soil surface to the 100 mm probe depth. In summer, soil temperature is appreciably higher in open land than in forest throughout the day due to solar heating of the soil surface (Lee, 1978).

Differences in air temperature and VPD were marked only under clear sky conditions, and the gradients for these variables from forest to pasture are minimal on cloudy days. Differences in wind speed, however, are expected whenever there is appreciable air movement, because of the wind-sheltering effect of the forest. Therefore gradients of microclimate are of greatest significance on sunny and windy days.

Microclimate gradients

The gradient of soil temperature is very abrupt near the forest edge and similar to that of light exposure. Chen *et al*. (1995) reported similarly abrupt gradients in soil temperature near Douglas fir forest edges. The pattern of soil temperature apparently mirrors that of light exposure because it is solar radiation that causes soil heating. In cleared land the surface soil receives most of the solar energy and, in turn, heats the air above it, whereas in forest the canopy intercepts most solar radiation so that there is little direct soil heating.

Wind speed, air temperature and VPD all exhibit more gentle spatial gradients near the forest edge than light and soil temperature, and therefore the former variables control the extent of edge influence on microclimate. We found that the microclimate gradients varied with wind direction. When wind was directed *out* of the forest there was little trend in air movement within the forest with distance from the edge. Under an outwards-directed wind, the air movement is caused by penetration of turbulence down through the canopy (Lee, 1978; Raynor, 1971). Under such conditions, air temperature and VPD also stabilised within a relatively short distance into the forest from the edge.

In contrast, when wind was directed *into* the forest, the air appeared to be driven as a "jet" into the trunk space. This phenomenon has been described by Raynor (1971) and modelled by Li *et al*., (1990). Such a jet may penetrate for a considerable distance, for example at least 60 m from the edge in Raynor's (1971) study of wind flow in and near a pine plantation. Our measurements suggest penetration of the wind jet, and associated air temperature and VPD, for at least 40 m from the edge with wind directed into the forest.

The distribution of ferns at our study site provides supporting evidence for this interpretation of the extent of edge influence. *Hymenophyllum* spp (filmy ferns) and *Leptopteris hymenophylloides* (A.Rich.) Presl. (Prince of Wales feather) are abundant more than c. 40 m into the forest, but are absent close to the edge, plausibly as a result of desiccation.

On two sets of transect measurements with wind directed out of the forest we detected a local elevation of air temperature (c. 2 ^{o}C) and VPD (c. 2 mB) close to the forest edge. A local "deadzone" of air created by the wind-sheltering effect of the forest, is the likely cause of this phenomenon. Chen *et al*. (1993) reported similar local extrema of air temperature and moisture at Douglas fir forest edges in the Pacific Northwest of USA. They asserted that forest edges should be recognised as a distinct micro-environment that is not always intermediate in conditions between adjacent interior forest and open land.

We did not explicitly consider aspect in this study, but others (e.g. Chen *et al*., 1993; Young and Mitchell, 1994) have studied the effect of aspect on microclimate. Aspect seems to have most influence on gradients of light exposure and associated soil temperature. Since the maximum extent of edge influence on microclimate is determined by air movement, we expect that the spatial extent of edge influence may be insensitive to aspect. However, we speculate that microclimatic exposure might be comparatively severe at west-facing forest edges in NZ since westerly winds that can "jet" into west-facing edges prevail in most areas of the country.

Chen *et al*. (1995) reported that edge effects on microclimate may penetrate as much as 240 m into Douglas fir forest, but in tropical rainforests the microclimate gradients seem to be appreciably steeper, particularly at mature edges. For example, Kapos (1989) and Camargo and Kapos (1995) reported that air temperature and relative humidity stabilised within 40 m of Brazilian rainforest edges and the gradients of these variables tended to become steeper with edge maturity. Williams-Linera (1990) reported that most of the change in these same microclimate variables occurred within 15 m of 5 year old edges in Panamanian rainforest.

Our finding of an edge influence on microclimate extending at least 40 m is closely comparable with that of Young and Mitchell (1994) who found that the edge influence on air temperature and VPD extended up to 50 m into podocarp-broadleaf forest remnants in Northland. Their findings on the extent of edge influence can now be extended to incorporate air movement (not measured by Young and Mitchell, 1994) as well as the temperature and drying capacity of air. However, we recognise that the extent of wind penetration and associated temperature and moisture changes may vary with site factors such as topography, edge canopy development, and foliage density of the shrub layer in forest.

Implications

Our finding that the edge effects on microclimate extend at least 40 m into native New Zealand rainforest has implications for both conservation of interior forest environments and for riparian buffers to protect streams. As we have seen, this finding is consistent with the work on edges of forest types that are broadly similar in foliage density and structure to New Zealand rainforest (Kapos, 1989; Williams-Linera, 1990; Turton and Freiburger, 1997). Our work is also consistent with that of Young and Mitchell (1994) who discussed ramifications for terrestrial ecology and indigenous species conservation in New Zealand of the 50 m wide edge zone that they inferred from their microclimate data. They suggested that native forest remnants < 9 ha

in area are dominated by edge microclimate conditions, and that remnants < 1 ha lack interior forest conditions. Here, we wish to consider the ramifications for the width of stream riparian buffers in New Zealand, following the approach taken in the USA (Forest Ecosystem Management Assessment Team, 1993; Brosofske *et al.*, 1997) based on microclimate studies by Chen and co-workers.

Because most (about 80%) of the New Zealand land area was originally heavily forested (Ministry for the Environment, 1997), much of our stream and riparian ecology probably evolved in forest conditions of dense shade and shelter from wind. Forest clearing may have exposed many stream and riparian organisms to increased climatic changeability and thermal and drying stress. For example, Collier and Smith (2000) have shown that adults of two species of native stoneflies, whose nymphs are common in NZ forest streams, are sensitive to temperature and humidity levels characteristic of unprotected riparian zones. Our microclimate work suggests that forest buffers c. 40 m wide may be needed on *both* sides of small streams to protect riparian ecology where the surrounding land use is open pasture or cropland. "Small streams" in this context are those < 3.5 m wide and which have light exposure comparable to the low levels of surrounding forest, implying an unbroken canopy above the channel (Davies-Colley and Quinn, 1998). Narrower buffers may be suitable in tree plantations where the adjoining land is only exposed for part of the timber crop rotation (i.e., after clear-cutting). Because microclimate variables asymptotically approach forest interior conditions with distance (e.g., Forest Ecosystem Management Assessment Team, 1993) there are diminishing returns for increased buffer width, however 40 m is proposed as a working guideline for protecting streams in New Zealand.

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