Austral Ecology (2000) **25**, 36–47

Grazing effects on plant cover, soil and microclimate in fragmented woodlands in south-western Australia: implications for restoration

COLIN J. YATES,[1]* DAVID A. NORTON[2] AND RICHARD J. HOBBS[3]
[1,3]*CSIRO Wildlife and Ecology, Wembley, Western Australia, Australia,* [2]*Conservation Research Group, School of Forestry, University of Canterbury, Christchurch, New Zealand*

Abstract This study investigated the impacts of livestock grazing on native plant species cover, litter cover, soil surface condition, surface soil physical and chemical properties, surface soil hydrology, and near ground and soil microclimate in remnant *Eucalyptus salmonophloia* F. Muell woodlands. Vegetation and soil surveys were undertaken in three woodlands with a history of regular grazing and in three woodlands with a history of little or no grazing. Livestock grazing was associated with a decline in native perennial cover and an increase in exotic annual cover, reduced litter cover, reduced soil cryptogam cover, loss of surface soil microtopography, increased erosion, changes in the concentrations of soil nutrients, degradation of surface soil structure, reduced soil water infiltration rates and changes in near ground and soil microclimate. The results suggest that livestock grazing changes woodland conditions and disrupts the resource regulatory processes that maintain the natural biological array in *E. salmonophloia* woodlands. Consequently the conditions and resources in many remnant woodlands may be above or below critical thresholds for many species. The implications of these findings for restoration of plant species diversity and community structure are discussed. Simply removing livestock from degraded woodlands is unlikely to result in the restoration of plant species diversity and community structure. Restoration will require strategies that capture resources, increase their retention and improve microclimate.

Key words: eucalypt woodlands, *Eucalyptus salmonophloia*, landscape function, livestock grazing, microclimate, restoration, soil water infiltration.

INTRODUCTION

Eucalypt woodlands in temperate southern Australia have been extensively cleared for agriculture and now occur as isolated patches that are often disturbed by livestock grazing (Goldney & Bowie 1990; Kirkpatrick & Gilfedder 1995; Prober & Thiele 1995; Yates & Hobbs 1997a). There is an increasing awareness of the important role these remnant woodlands play in regional conservation networks (Prober 1996; Prober & Thiele 1995; Howling 1996; Robinson & Traill 1996). However, under current management many of these remnants are unlikely to persist without some form of restoration (Goldney *et al.* 1995; Yates & Hobbs 1997a, b).

It is well established that grazing by domestic livestock can be a major degrading process in temperate eucalypt woodlands (Moore 1970; Adamson & Fox 1982; Lunt 1991; Petit *et al.* 1995; Prober & Thiele 1995; Abensperg-Traun *et al.* 1996; Yates & Hobbs 1997a). The most obvious effect of livestock grazing is a change to vegetation structure and composition; certain species increase in abundance, while other species decrease. Changes in the composition and structure of temperate grassy woodlands in south-eastern Australia have been described by Moore (1970), Lunt (1991), Sivertsen (1993) McIntyre and Lavorel (1994), and Prober and Thiele (1995). Overall, increases in the diversity of native species have been recorded at light to moderate levels of grazing, while declines occur at very high and very low grazing intensities (Prober & Thiele 1993, 1995; McIntyre & Lavorel 1994; Tremont & McIntyre 1994). Generally, as livestock grazing pressure increases, native plant species become less abundant and are replaced by exotic species. Grazing by cloven-hoofed livestock may also have a major impact on soil structure and the soil regulatory processes that provide plants with water and nutrients. There is little published evidence to quantify these effects in temperate woodlands. However, in Australian rangelands the removal of perennial vegetation cover by livestock grazing and trampling by hard hooves is known to cause loss of litter cover, loss of soil cryptogams, reduced organic carbon, loss of nutrients, loss of soil microtopography, soil compaction, reduced soil water infiltration rates, increased soil

---

*Correspondence address: Dr Colin J. Yates, Western Australian Herbarium, Department of Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, WA 6983, Australia (coliny@calm.wa.gov.au).

Accepted for publication June 1999.

surface erosion and consequently loss of ecosystem functions which capture and cycle scarce limiting resources such as water and nutrients (Braunack & Walker 1985; Graetz & Tongway 1986; Greene & Tongway 1989; Greene 1992; Eldridge & Koen 1993; Ludwig *et al.* 1994; Tongway & Ludwig 1994).

The degradation of soil structure and loss of ecosystem functions may have important consequences for the restoration of plant species diversity. Yates and Hobbs (1997b) hypothesized that long-term grazing by livestock could shift the woodland system to a degraded state, this shift being difficult to reverse. Soil compaction impedes root growth and therefore reduces the ability of the roots to provide the plant with water and nutrients. Soil compaction also reduces water infiltration rates and therefore reduces soil water recharge. As a consequence, soil water availability may be far more limiting in heavily grazed degraded woodlands than in ungrazed woodlands, with obvious implications for plant growth, reproduction and seedling establishment. Attempts to restore plant species diversity and habitat structure to degraded woodlands therefore are less likely to succeed if soil structural decline and changes to resource regulatory processes have occurred. In the terminology employed by Yates and Hobbs (1997b) a management/restoration threshold may have been crossed, and significant effort is required to reverse the degradation.

Currently there is little known about the impact of livestock grazing on soil structure and resource regulatory processes in temperate eucalypt woodlands. Clearly this information is needed to test the hypothesis of restoration thresholds and to plan effective restoration strategies. This study therefore aims to do the following.

- Assess the effects of livestock grazing and trampling on native plant species cover, litter cover, and surface soil physical and chemical properties.
- Assess the impact of changes to the above parameters on soil and landscape resource regulatory processes such as infiltration rate, soil water storage, nutrient status and cycling, soil stability, and near ground and soil microclimates.
- Provide information for developing strategies that restore the soil processes that sustain native plant species in degraded woodlands; and provide baseline information on rates of soil and landscape resource regulatory processes against which the success of restoration can be assessed.

METHODS

Study sites

The study was conducted in remnant *Eucalyptus salmonophloia* woodlands north of Kellerberrin and east of Merredin in the central wheatbelt of Western Australia approximately 200 km east of Perth. The region is a wheat and sheep farming district and has a Dry Warm Mediterranean climate with mean annual rainfall ranging from 334 mm at Kellerberrin to 307 mm at Merredin. Rain falls predominantly in the winter months between May and September. Summer rainfall occurs but is unpredictable.

In this region remnant *E. salmonophloia* woodlands are most extensive on the broad valley floors on red brown sandy loam over clay (Db 1.13, Dr 2.13) and red brown clay soils (Gc 2.21, Uf 6.31, Db 1.13), but they also occur to a lesser extent on mid and upper slopes on grey, brown or dull reddish loamy sand over clay (Dy 2.13, Dy 2.23) (McArthur 1991; Lantzke 1992).

Three woodlands regularly grazed by sheep in the past (heavily grazed) and three woodlands very occasionally or never grazed (rarely grazed/ungrazed) were chosen for comparisons of vegetation cover, soil surface condition, soil chemical attributes, soil bulk density, soil penetration resistance, soil hydraulic properties, and near ground and soil microclimates. The three heavily grazed woodlands are in farm paddocks and are grazed by sheep when the paddocks are not being cropped. A typical rotation is a cereal crop followed by two years of grazing (Nulsen 1992). Typical stocking rates for the area are in the order of seven sheep per hectare (Proffitt *et al.* 1993). Crop and grazing rotations have probably occurred since the 1930s when sheep were introduced to farms in the region (Main 1992). The three rarely grazed/ungrazed woodland remnants are in reserves that have different conservation status. Two of the sites are in a former water reserve but are now leased and are open to sheep once a year for brief periods (one or two days) following shearing. The third rarely grazed/ungrazed site occurs in a nature reserve and has no known recent history of livestock grazing. The heavily grazed and rarely grazed woodlands are strikingly different visually.

All sites were located on valley floors on red brown sandy loam over clay soils. These soils have been described in detail by McArthur (1991) and Lantzke (1992). At each site two 50 m transects spaced 5 m apart were established, and ten 1 m^2 quadrats at 5 m intervals were located in each transect.

Vegetation cover

At each site in September 1996 (spring) the percentage cover of exotic annuals, native annuals and native perennial herbs and shrubs was assessed visually in each quadrat.

Soil surface condition

Soil surface condition was assessed at all sites using the methods described by Tongway (1994). Perennial shrub and herb cover, crypotogam cover, erosion features (presence of rills and gullies, terracettes, sheeting and scalding), lag materials, litter characteristics, soil microtopography and nature of soil surface were measured in the 20 quadrats at each site.

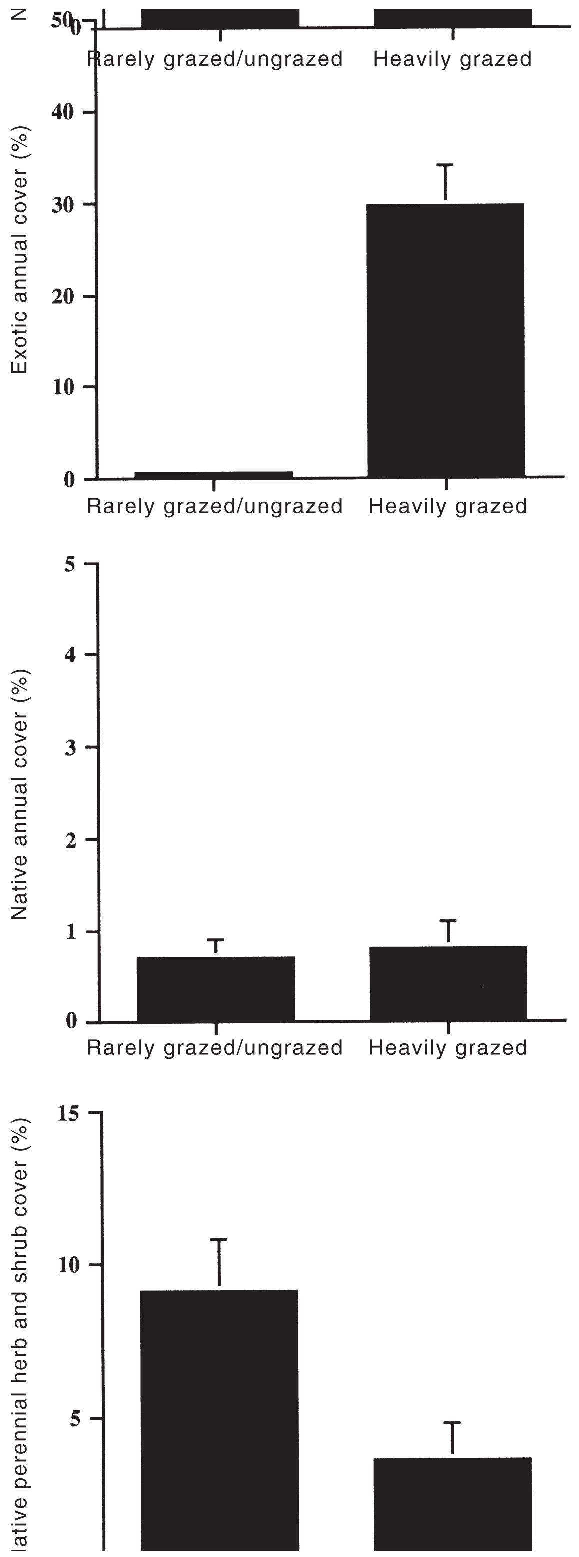

Fig. 1. Mean percentage cover in 1 m^2 quadrats ($n = 60$) of exotic annuals, native annuals and native perennial herbs and shrubs in rarely grazed/ungrazed and heavily grazed remnant *Eucalyptus salmonophloia* woodlands. Vertical bars represent standard errors of means.

Soil chemical properties

At each site two soil cores 20 mm deep and 40 mm in diameter were taken adjacent to the opposite corners of each quadrat. Cores for each site were bulked, mixed thoroughly, air dried and stored in airtight containers. Five subsamples from each bulked sample were taken for chemical analysis. The analyses were performed by CSBP laboratories for the following parameters:

- NO_3^- nitrogen
- NH_4^+ nitrogen
- extractable phosphorous
- extractable potassium
- organic carbon
- electrical conductivity
- pH
- exchangeable cations (Ca^{+2}, Mg^{+2}, Na^+, K^+)

The ammonium and nitrate nitrogen were measured simultaneously using a Lachet flow injection analyser. Soils were tumbled with 1 mol L^{-1} potassium chloride solution for 1 h at 25°C using a soil/solution ratio of 1 : 5. The concentration of ammonium nitrogen was measured colourimetrically at 420 nm using the indophenol blue reaction. The nitrate was reduced to nitrite through a copperized-cadmium column and the concentration of nitrite measured colourimetrically at 520 nm. Available phosphorous and potassium were measured using the Colwell method; soils were tumbled with a 0.5 mol L^{-1} sodium bicarbonate solution adjusted to pH 8.5 for 16 h at 25 °C using a soil/solution ratio of 1 : 100. The acidified extract was treated with ammonium molybdate-antimony trichloride reagent and the concentration of phosphate measured colourimetrically at 880 nm. The concentration of potassium was determined using a flame atomic absorption spectrophotometer, at 766.5 nm. Organic carbon was determined by chromic acid digestion and measured colourimetrically at 600 nm. Soil pH and electrical conductivity were determined on an extract from a 1 : 5 soil/ deionised water suspension which had been stirred for 1 h at 25°C.

Soil physical properties

At each site soil bulk density values were determined using 20 mm long, 40 mm diameter steel cores driven into the soil surface adjacent to each quadrat. Soil cores were oven-dried at 90°C and bulk density calculated. Soil surface resistance measurements were taken immediately adjacent to each quadrat with an Eijkelkamp hand penetrometer. The maximum force required to push a 1cm^2 or 3.33cm^2 basal area cone vertically to a depth of 0–20 mm and 0–40 mm was recorded and the corresponding resistance (MPa) calculated.

Soil hydraulic properties

Infiltration measurements were made adjacent to five randomly chosen quadrats at each site. Measurements were made with a disc permeameter (200 mm

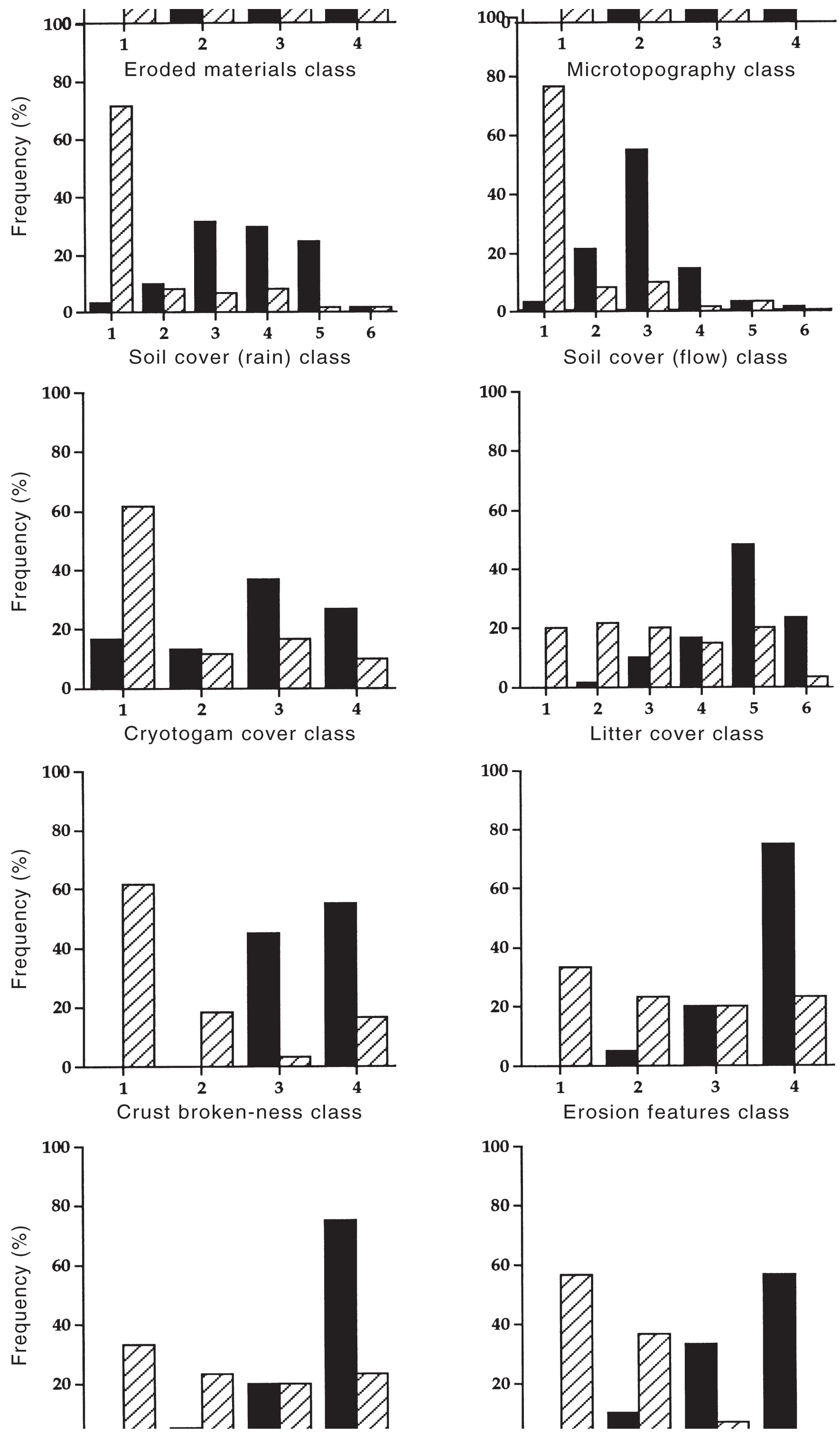

Fig. 2. Percentage frequency of soil cover (rain), soil cover (flow), cryptogam cover, litter cover, crust brokenness, erosion features, eroded materials and microtopography classes in rarely grazed/ungrazed (▨) and heavily grazed (■) remnant *Eucalyptus salmonophloia* woodlands. For soil cover (rain), soil cover (flow), cryptopgam cover, litter cover and microtopography, higher classes represent greater cover or abundance of the attribute. For crust brokenness, erosion features and eroded materials higher classes represent lower cover or abundance of the attribute.

diameter) that supplied water at a potential of +10 mm. Where necessary, vegetation was cut back to the soil surface and leaf litter removed. The permeameters were left to run until a constant infiltration rate was achieved, usually after 20–30 min. Steady state infiltration rates were calculated using the methods described by Perroux and White (1988).

Near ground and soil microclimates

One heavily grazed site and one very rarely grazed site were chosen for comparisons of near ground and soil microclimate. At each site four 5 m × 5 m contiguous quadrats configured in a 10 m × 10 m square were located in areas that had similar densities and cover of *E. salmonophloia*.

In each quadrat at a randomly chosen point the following microclimate parameters were measured:

- wind speed at 0.4 m using a Vector Instruments A101M anemometer
- relative humidity and air temperature at 0.4 m using Skye SKH2011 and Campbell 207 RH/temperature sensors
- shaded ground surface temperature using a Campbell 107 temperature probe
- soil temperature at 10 cm depth using a Campbell 107B temperature probe

Measurements were made at 10 s intervals and stored as 30 min averages. Wind speed was measured as 30 min maximums, using Campbell 21X and CR10 data loggers.

Microclimates were measured simultaneously in the two remnants for 7-day periods in February/March 1993 (late summer) and June 1993 (winter) with

Table 1. Values of soil nutrient concentrations (mean ± SE; *n* = 15) in rarely grazed/ungrazed and heavily grazed remnant *Eucalyptus salmonophloia* woodlands

Soil attribute	Rarely grazed/ ungrazed	Heavily grazed	*P*
NNO_3^- mg kg^{-1}	4.07 ± 0.68^a	14.08 ± 3.5^b	*
NH_4^+ mg kg^{-1}	3.40 ± 0.16^a	8.20 ± 1.4^b	*
PO_4^{-3} mg kg^{-1}	10.40 ± 0.88^a	25.07 ± 2.1^b	**
K^+ mg kg^{-1}	533 ± 31^a	388 ± 33^b	*
Organic C percentage	1.43 ± 0.08^a	1.14 ± 0.03^b	*
E. C. dS m^{-1}	0.11 ± 0.01^a	0.14 ± 0.03^a	NS
pH	7.88 ± 0.16^a	6.78 ± 0.04^b	**
Ca^{+2} meq $100g^{-1}$	10.76 ± 1.1^a	4.90 ± 0.31^b	**
Mg^{+2} meq $100g^{-1}$	3.14 ± 0.24^a	2.95 ± 0.09^a	NS
Na^+ meq $100g^{-1}$	0.28 ± 0.02^a	0.77 ± 0.07^b	**
K^+ meq $100g^{-1}$	1.58 ± 0.11^a	1.06 ± 0.10^b	*

Means followed by the same letter are not significantly different (*$P < 0.01$, **$P < 0.001$). Data were analysed with unpaired two-tailed *t* -tests.

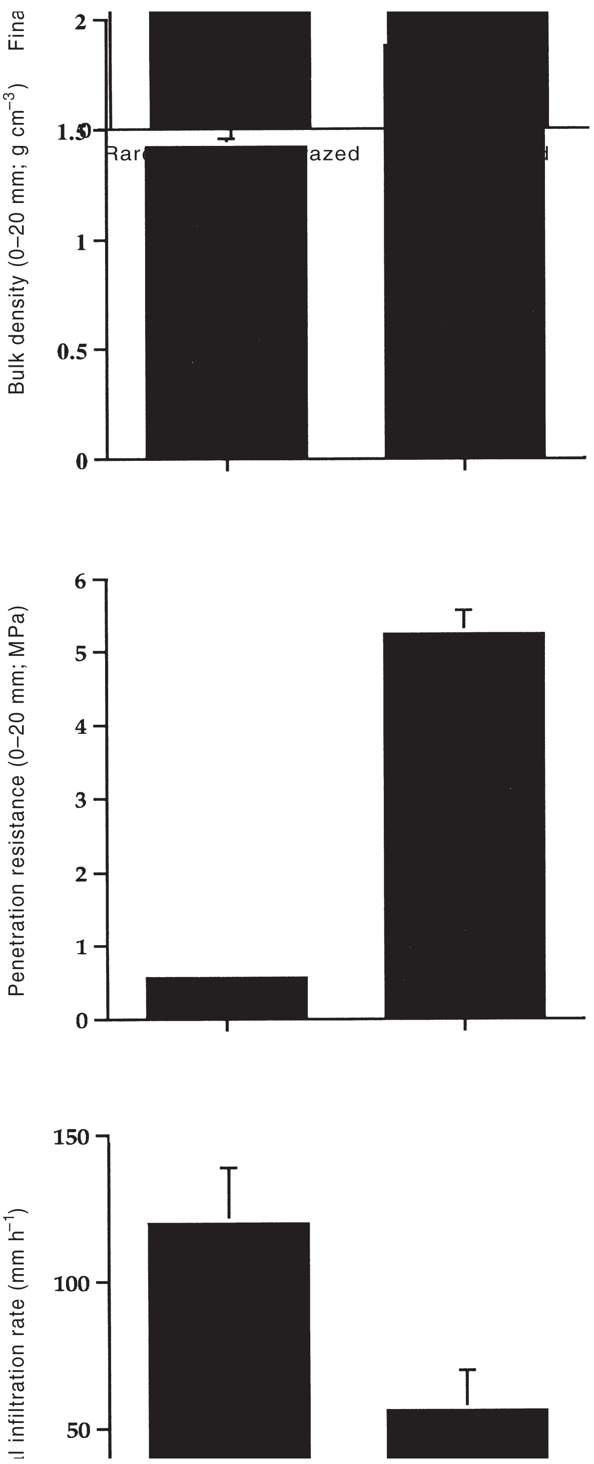

Fig. 3. Mean soil bulk density (0–20 mm; *n* = 60), penetration resistance (0–20 mm; *n* = 60) and soil water infiltration rates (*n* = 15) in rarely grazed/ungrazed and heavily grazed *Eucalyptus salmonophloia* woodlands. Vertical bars represent standard errors of means.

Table 2. Climate variables (mean ± SD), February/March 1993, with significant differences (based on the repeated measures ANOVA, $P < 0.05$) between grazed and ungrazed sites indicated by different letters

	Air temperature (°C)	Surface temperature (°C)	Soil temperature (°C)	Relative humidity (%)	Mean wind speed (ms^{-1})	Max wind speed (ms^{-1})
Sample size	28	28	21	28	20	20
Daily means						
grazed	26.3 ± 2.06^{a}	27.1 ± 1.98^{a}	29.9 ± 1.75^{a}	33.7 ± 9.22^{a}	0.76 ± 0.129^{a}	1.82 ± 0.265^{a}
ungrazed	25.2 ± 1.96^{b}	25.4 ± 1.90^{b}	24.7 ± 0.70^{b}	37.0 ± 9.77^{a}	1.01 ± 0.622^{a}	2.25 ± 1.213^{a}
Daily ranges						
grazed	27.4 ± 2.77^{a}	23.8 ± 2.72^{a}	15.1 ± 3.40^{a}	54.9 ± 13.51^{a}	1.32 ± 0.434^{a}	3.11 ± 0.481^{a}
ungrazed	23.4 ± 5.15^{a}	22.3 ± 3.56^{a}	3.9 ± 2.24^{b}	51.7 ± 12.50^{a}	1.41 ± 0.614^{a}	2.91 ± 1.365^{a}
Daytime means						
grazed	38.8 ± 3.13^{a}	37.9 ± 3.22^{a}	36.1 ± 3.06^{a}	12.2 ± 4.44^{a}	1.04 ± 0.129^{a}	3.22 ± 0.336^{a}
ungrazed	34.6 ± 3.69^{b}	33.7 ± 2.88^{b}	25.7 ± 0.95^{b}	18.4 ± 6.90^{a}	1.16 ± 0.548^{a}	3.39 ± 1.629^{a}
Night-time means						
grazed	17.2 ± 1.58^{a}	19.2 ± 1.36^{a}	25.8 ± 1.63^{a}	54.6 ± 15.10^{a}	0.60 ± 0.215^{a}	2.44 ± 0.881^{a}
ungrazed	17.0 ± 1.61^{a}	17.5 ± 1.59^{b}	23.8 ± 0.82^{a}	57.3 ± 14.52^{a}	0.94 ± 0.750^{a}	2.94 ± 1.828^{a}

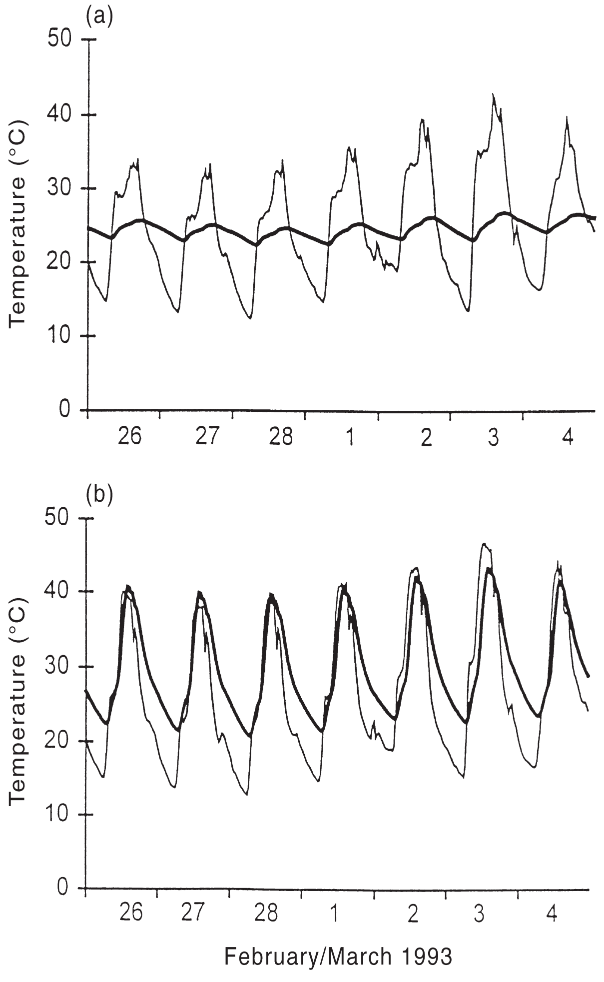

Fig. 4. Daily air (—) and soil (**—**) temperature patterns for one microclimate sampling point at the (a) ungrazed and (b) grazed sites during the February/March measurement period. *X*-axis ticks are at midnight.

the same sampling points being used in both seasons.

It is acknowledged that the microclimate quadrats within the two remnants are pseudoreplications. Unfortunately it was necessary to restrict measurements within the two remnants because of the expense and the amount of monitoring equipment available for the study.

Statistical analyses

Comparisons of vegetation cover, soil chemical properties, bulk density, penetration resistance and infiltration rate were made with unpaired two tailed *t*-tests on data pooled across heavily grazed and very rarely grazed sites. Assumptions of normality and homogeneity of variance were checked and found to be valid.

The 30 min measurements of mean air temperature, mean ground surface temperature, mean soil temperature, mean relative humidity, mean windspeed, maximum wind speed and the standard deviation of windspeed were summarised to produce four sets of daily values; these were mean daily values, daily range (maximum-minimum), daytime mean and night-time mean. Daytime was defined as the period from 11.30 to 17.30 hours in February/March and 10.00–16.00 hours in June, and night-time as the period from 00.00 to 06.00 hours in both February/March and June. These times were chosen as representative of the time periods with maximum temperature and minimum relative humidity, and minimum temperature and maximum relative humidity, respectively. Comparisons of microclimate at the heavily grazed and rarely grazed/ungrazed sites were assessed using repeated measures analysis of variance (Green 1993).

RESULTS

Vegetation cover

The percentage cover of exotic annuals was significantly higher in heavily grazed remnant *E. salmonophloia* woodlands than in rarely grazed/ungrazed woodlands ($t = -6.608$, d.f. = 118, $P < 0.0001$). The mean percentage cover of exotic annuals in heavily grazed woodlands was 29.7% and in rarely grazed/ungrazed woodlands was 0.5% (Fig. 1). Conversely the percentage cover of native perennials was significantly higher in rarely grazed/ungrazed woodlands than in heavily grazed woodlands ($t = 2.639$, d.f. = 118, $P < 0.008$). The mean percentage cover of native perennials in rarely grazed/ungrazed woodlands was 9.1% and in heavily grazed woodlands was 3.6% (Fig. 1). No significant differences in native annual cover were observed between different grazing regimes (Fig. 1).

Soil surface condition

Soil surface conditions were degraded in heavily grazed remnants (Fig. 2). The cover of perennial shrubs and herbs in heavily grazed woodlands was consistently less than in rarely grazed/ungrazed woodlands. The cover of objects that project at least 1–2 cm above the soil surface (plant stems, grass tussocks, rocks and sticks >6 mm in diameter) in heavily grazed woodlands was consistently less than in rarely grazed/ungrazed woodlands. Soils in heavily grazed woodlands were therefore much more susceptible to erosion than in rarely grazed/ungrazed woodlands. Cryptogam cover and litter cover in heavily grazed woodlands were consistently less than in rarely grazed/ungrazed woodlands. Not surprisingly measures of soil surface erosion; crust brokenness, presence of erosion features, presence of eroded materials and loss of soil microtopography in heavily grazed woodlands were consistently higher than in rarely grazed/ungrazed woodlands.

Soil chemical properties and particle size analyses

Concentrations of soil nitrate-nitrogen, ammonium-nitrogen, available phosphorous and exchangeable sodium were significantly higher in heavily grazed woodlands than in rarely grazed/ungrazed woodlands (Table 1). Conversely, concentrations of available potassium, organic carbon, exchangeable calcium, exchangeable potassium and soil pH were significantly higher in rarely grazed/ungrazed woodlands than in heavily grazed woodlands (Table 1). No significant differences in electrical conductivity and exchangeable magnesium were observed between the different grazing treatments (Table 1).

Soil physical properties

Surface soil bulk density was significantly higher in heavily grazed remnant *E. salmonophloia* woodlands than in rarely grazed/ungrazed woodlands ($t = 9.98$, d.f. = 118, $P < 0.0001$). Mean soil bulk density in heavily grazed woodlands was 1.88 g cm^{-3} and in rarely grazed/ungrazed woodlands was 1.42 g cm^{-3} (Fig. 3). Soil penetration resistance in the 0–20 mm fraction was 10 times greater in heavily grazed woodlands than in rarely grazed/ungrazed woodlands ($t = 13.96$, d.f. = 118, $P < 0.0001$). The mean penetration resistance in heavily grazed woodlands was 5.24 MPa and in rarely grazed/ungrazed woodlands was 0.56 MPa (Fig. 3). Similarly, soil penetration resistance in the 0–40 mm fraction was significantly greater in heavily grazed woodlands than rarely grazed/ungrazed woodlands ($t = 15.67$, d.f. = 118, $P < 0.0001$). Mean penetration resistance in heavily grazed woodlands was 5.89 MPa and in rarely grazed/ungrazed woodlands was 1.10 MPa (Fig. 3).

Soil hydraulic properties

Steady state infiltration rates in rarely grazed/ungrazed woodlands were double that in heavily grazed woodlands ($t = 2.73$, d.f. = 28, $P < 0.01$). Mean steady state infiltration rate in rarely grazed/ungrazed woodlands was 120 mm h^{-1} and in heavily grazed woodlands was 56 mm h^{-1} (Fig. 3).

February/March microclimates

Summary data for air temperature, ground surface temperature, soil temperature, relative humidity, and mean and maximum wind speed are presented in Table 2, with significant differences between sites indicated. Significant differences between days, and in the site×days interaction were also found, reflecting differences in weather conditions during the measurement period. The 7-day study period was characterized by clear fine weather with steadily increasing air temperature and decreasing relative humidity until 3 March, when a southerly front crossed the area raising the humidity and decreasing the temperature. Air temperatures generally ranged from a minimum of about 15°C to greater than 40°C, while relative humidity varied widely on a daily basis, from night-time highs of 40–80% to daytime lows of <10%.

Mean daily air temperature was significantly different between the grazed and rarely grazed/ungrazed sites (Table 2), reflecting a significant difference in daytime means. However, there was no significant difference in night-time means or in the daily temperature range. Ground surface temperatures showed a similar pattern

(Table 2), except there was also a significant difference in night-time temperatures between the grazed and rarely grazed/ungrazed sites (Table 2), with the grazed site being warmer.

Soil temperatures showed the most dramatic differences between the grazed and rarely grazed/ungrazed sites, with the soils in the grazed woodland being significantly warmer than the soils in the rarely grazed woodland (Table 2). This difference is particularly striking during daytime when mean temperatures in grazed soils were 36.1°C (cf. 25.7°C in the ungrazed situation) and where maximum temperatures reached 48.3°C, with temperatures commonly in excess of 40°C. There was also a highly significant difference in the daily range of soil temperatures between the grazed and rarely grazed sites (Table 2). Ground surface and air temperatures follow similar daily patterns. Soil temperatures at the rarely grazed site are strongly modulated but those at the grazed site follow the air temperatures much more closely (Fig. 4), although night-time soil temperatures are higher than in the air or at the ground surface.

There were no significant differences between the grazed and rarely grazed sites in mean daytime or night-time relative humidities (Table 2). Wind speeds were quite variable with no significant grazed-rarely grazed/ungrazed differences (Table 2), although daytime wind speeds were consistently higher than night-time wind speeds.

June microclimates

Summary data for air temperature, ground surface temperature, soil temperature, relative humidity, and mean and maximum wind speed are presented in Table 3, with significant differences between sites indicated. Significant differences between days, and in the site ×days interaction were also found, reflecting differences in weather conditions during the measurement period. The 7-day study period was characterised by a mixture of clear fine weather and partly cloudy days, with colder wetter weather on 16 June. Air temperatures generally ranged from close to 0°C to about 20°C, while relative humidities were usually in excess of 80% at night dropping to 40% during the day.

Mean daily air temperature was significantly different between the grazed and rarely grazed/ungrazed sites (Table 3), reflecting significant differences in both daytime and night-time means. However, there was no significant difference in the daily temperature range. Ground surface temperatures showed a similar pattern (Table 3), except daytime temperatures were not significantly different between the grazed and rarely grazed/ungrazed sites (Table 3).

Soil temperatures again showed marked differences between the grazed and rarely grazed/ungrazed sites, with the soils in the grazed woodland being significantly warmer than the soils in the rarely grazed/ungrazed woodland (Table 3). The most marked difference was in the daily temperature range, which was 8.6°C at the grazed site and 2.7°C at the rarely grazed/ungrazed site. However, unlike February/March, soil temperatures in the grazed and rarely grazed/ungrazed sites were significantly different at night-time as well as daytime (Table 3). As with the February/March data, soil temperatures at the grazed site appear strongly coupled with air and ground surface temperatures, while soil temperatures at the rarely grazed/ungrazed site are again strongly modulated (Fig. 5).

Daytime relative humidity was significantly different between the grazed and rarely grazed/ungrazed sites, but night-time differences were not significant (Table 3). There were also significant differences in the daily

Table 3. Climate variables (mean ± SD), June 1993, with significant differences (based on the repeated measures ANOVA, $P < 0.05$) between grazed and ungrazed sites indicated by different letters

	Air temperature (°C)	Surface temperature (°C)	Soil temperature (°C)	Relative humidity (%)	Mean wind speed (ms^{-1})	Max wind speed (ms^{-1})
Sample size	28	28	21	28	20	20
Daily means						
grazed	11.9 ± 0.46^{a}	12.4 ± 0.68^{a}	12.0 ± 0.83^{a}	77.7 ± 6.44^{a}	0.82 ± 0.388^{a}	1.69 ± 0.453^{a}
ungrazed	11.2 ± 0.81^{b}	10.8 ± 0.76^{b}	12.7 ± 0.44^{a}	78.0 ± 6.67^{a}	0.50 ± 0.230^{b}	1.23 ± 0.432^{b}
Daily ranges						
grazed	13.2 ± 5.18^{a}	8.7 ± 5.42^{a}	8.6 ± 4.70^{a}	45.5 ± 13.26^{a}	1.81 ± 1.044^{a}	3.24 ± 1.318^{a}
ungrazed	12.3 ± 5.90^{a}	10.2 ± 4.95^{a}	2.7 ± 2.09^{b}	37.4 ± 12.91^{b}	1.02 ± 0.269^{b}	2.29 ± 0.753^{b}
Daytime means						
grazed	17.6 ± 3.02^{a}	15.8 ± 2.36^{a}	15.7 ± 2.32^{a}	58.6 ± 16.98^{a}	1.35 ± 0.895^{a}	2.60 ± 1.099^{a}
ungrazed	16.1 ± 2.62^{b}	14.9 ± 2.14^{a}	13.3 ± 0.57^{b}	64.2 ± 15.57^{b}	0.84 ± 0.327^{b}	1.86 ± 0.590^{b}
Night-time means						
grazed	8.5 ± 2.02^{a}	10.2 ± 1.59^{a}	9.7 ± 1.84^{a}	88.1 ± 8.02^{a}	0.66 ± 0.534^{a}	1.41 ± 0.698^{a}
ungrazed	7.8 ± 3.05^{b}	7.9 ± 2.52^{b}	12.0 ± 0.86^{b}	86.1 ± 7.02^{a}	0.36 ± 0.299^{b}	0.96 ± 0.617^{b}

relative humidity range, with this being greater for the grazed site (Table 3). Wind speeds also showed significant differences between the grazed and rarely grazed/ungrazed sites in June (Table 3), although mean wind speeds were similar to those in February/March. Daily, daytime and night-time mean and maximum wind speeds were all significantly greater at the grazed site, and the daily range was also greater at grazed sites (Table 3).

DISCUSSION

Livestock grazing is a composite disturbance that encompasses the effects of defoliation, trampling, defecation and urination (Wilson 1990; Abensperg-Traun *et al.* 1996; Yates & Hobbs 1997a). The results presented here demonstrate that livestock grazing in remnant *E. salmonophloia* woodlands has an impact not only on vegetation structure and composition but also on soil surface condition, soil chemical, physical and hydrological properties, and near ground and soil microclimate. These effects may have important consequences for restoration of plant species diversity and community structure in remnant eucalypt woodlands.

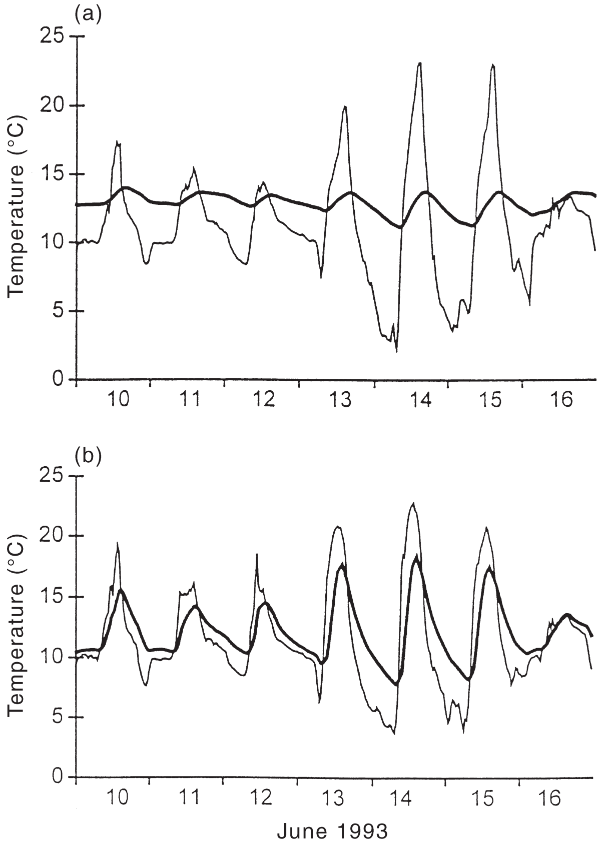

Fig. 5. Daily air (—) and soil (**—**) temperature patterns for one microclimate sampling point at the (a) ungrazed and (b) grazed sites during the June measurement period. Data from the same microclimate measurement sampling point as used in Fig. 4. *X*-axis ticks are at midnight.

Livestock grazing in remnant *E. salmonophloia* woodlands was associated with the loss of features that protect the soil surface from rain splash erosion and obstruct or divert overland flow. Soils in heavily grazed remnants were therefore more susceptible to erosion and loss of soil surface stability. In rarely grazed/ungrazed woodlands the soil surface had a greater cover of perennial shrubs and herbs, logs, other woody debris, litter and cryptogams, high levels of microtopography and little erosion. By contrast grazed woodlands had little or no cover of perennial shrubs and herbs, logs, other woody debris, litter and cryptogams, low levels of microtopography and high levels of erosion with evidence of sheet erosion being common.

Similarly livestock grazing had a major impact on soil chemical properties. The higher concentrations of soil nitrate-nitrogen, ammonium-nitrogen and available phosphorous in heavily grazed woodlands may be a consequence of livestock grazing in the surrounding agricultural landscape and defecating and urinating in the remnant. Scougall *et al.* (1993) observed that this pathway had a significant impact on the nutrient status of *Eucalyptus loxophleba* woodlands in south-western Australia. However, nutrient enrichment can also occur when fertilisers applied to farmland are redistributed to remnant woodlands as a result of drift during application and direct run-off (Cale & Hobbs 1991; McIntyre & Lavorel 1994). The lower concentrations of available potassium, organic carbon, exchangeable calcium and exchangeable potassium and the lower soil pH in heavily grazed woodlands may be a consequence of reduced inputs of litter and reduced availability of organic materials for decomposition and nutrient cycling.

Livestock grazing also had a major impact on soil surface structure and hydrology. The higher soil bulk density and increased soil penetration resistance in heavily grazed woodlands reflect reduced pore volume and may be due to the loss of perennial vegetation cover and soil cryptogams, and the impact of sheep trampling. Perennial vegetation cover is important for two reasons: (i) there is a positive feedback from plants to the soil in the form of organic materials for decomposition and nutrient cycling, and (ii) vegetation cover protects the soil surface from raindrop splash and surface sealing effects. Both of these factors result in the soil having improved physical properties. Soils with higher organic matter content usually contain more stable aggregates and undergo less slaking in water (Tisdall & Oades 1982; Greene & Tongway 1989; Greene 1992). The lower concentrations of soil organic carbon in heavily grazed remnants probably contribute to soil aggregates being less stable and more susceptible to breaking down under raindrop splash. Sheep trampling, when soils are wet, may also break down soil aggregates; soil pressures from sheep hooves might be as much as 200 kPa (Willatt & Pullar 1983). Hamblin (1984) found, on a soil similar to the soil type in this study, that surface aggregates readily slaked when immersed dry into water and dispersed as well as slaked after remoulding. This suggests that the soil surface in remnant *E. salmonophloia* woodlands is susceptible to dispersion and loss of surface pores through the remoulding action of sheep hooves on the soil. This is no doubt exacerbated in heavily grazed woodlands by reduced soil aggregate stability due to lower levels of organic carbon.

Not surprisingly the loss of porosity in the surface soil in heavily grazed woodlands affected surface soil hydrology. Rates of soil water infiltration in heavily grazed woodlands were half that in rarely grazed/ungrazed woodlands. Proffitt *et al.* (1993) working on the same soil type in agricultural land also reported reduced infiltration rates following sheep grazing.

Livestock grazing had significant impact on microclimate affecting air temperature, soil surface temperature, soil temperature, wind speed and relative humidity. The impact of livestock grazing on soil temperature was significant. Soils in the grazed woodland were significantly warmer than in the ungrazed woodland especially in summer with temperatures commonly in excess of 40 °C. The daily range in soil temperature in the grazed woodland was also significantly greater than in the ungrazed woodland where soil temperature was highly modulated. These observations are best explained by the loss of foliage and litter cover leading to an increase in the exposure of the soil surface to radiation and compaction, facilitating the rapid conduction of heat through the soil, and resulting in higher daytime and lower night-time temperatures. The loss of foliage and litter cover and increased daytime temperatures are likely to contribute greater evaporative loss from the soil surface.

The results presented here suggest that livestock grazing changes conditions and disrupts the resource regulatory processes which maintain the natural biological array in *E. salmonophloia* woodlands. As a consequence, conditions and resources in remnant woodlands may be above or below critical thresholds for many species, which has important implications for the restoration of plant species diversity and community structure. For example, higher and lower soil temperatures and reduced soil water availability may affect temperature and moisture dependent processes such as seed germination and nutrient cycling processes, which occur at or near the soil surface. Moreover, altered soil hydraulic properties and surface water hydrology may have serious consequences for perennial plant growth in a Dry Mediterranean climate where water is a scarce resource. Reduced soil water infiltration and extensive erosion indicate that rainfall is flowing out of grazed woodlands into surrounding agricultural land. As a consequence, soil water recharge, soil water storage and soil water availability are likely to have declined in grazed remnants and may be below critical thresholds for seed germination, seedling establishment and subsequent growth and reproduction in many perennial plant species. Indeed, Yates (1995) observed that soil water availability was the most important factor limiting the early growth of *E. salmonophloia*. Attempts to restore plant species diversity and community structure in degraded woodlands are therefore unlikely to succeed without the repair of the dysfunctional ecosystem processes that are resulting in the external flow of scarce resources.

An understanding of the way in which resources are captured, distributed and cycled in the undegraded ecosystem is important in this respect. Recent studies of landscape organisation and function in the semi-arid eucalypt and mulga woodlands of eastern Australia have shown a pattern of fertile patches across the landscape, where soil nutrient availability, soil water availability and soil stability are higher (Tongway & Ludwig 1990, 1993; Tongway 1991; Ludwig & Tongway 1995; Ludwig *et al.* 1997). The accumulation of resources in these patches may be in part due to terrain features and in part due to biological features, which slow down or intercept water, soil and litter as they flow or blow around the landscape. This process of resource concentration operates at a range of scales with tree canopies, logs and other woody debris, shrubs and grass tussocks acting as sinks. The spatial organisation of fertile patches acting as resource filters has the overall function of conserving limited resources within the ecosystem.

The features that these studies describe as components of resource sinks are some of the main differences between the heavily grazed and rarely grazed/ungrazed sites in the current study. For example, the cover of perennial shrubs and herbs, plant stems, grass tussocks and woody material (to trap resources) was consistently less in the grazed woodlands than in rarely grazed/ungrazed woodlands.

Livestock grazing in remnant woodland has removed the landscape patchiness and reduced the probability of resource sinks forming. It would therefore be reasonable to expect lower levels of resources in grazed woodlands. Indeed, measurements of reduced water infiltration, litter cover, soil organic carbon and some nutrients support this expectation. Interestingly, concentrations of soil ammonium-nitrogen, nitrate-nitrogen and available phosphate were higher in grazed woodlands. This may be attributable to livestock bringing nutrients into the system from surrounding landscapes, in the form of urine and faeces.

An essential component of a restoration program is to reduce the loss of resources from remnants by increasing the potential for sinks to develop. Strategies which increase soil surface roughness, such as deep ripping, and adding above ground obstructions, such as woody debris, may be useful in this respect (Whisenant *et al.* 1995; Tongway & Ludwig 1996). In the short term, the suggested treatments improve hydrologic and nutrient cycling processes by capturing water, soil, nutrients and organic materials (Whisenant *et al.* 1995; Tongway & Ludwig 1996). Moreover, above ground obstructions such as tree branches and foliage may also improve soil microclimate creating more favourable microhabitat for soil fauna. Tongway & Ludwig (1996) observed that branches laid onto a degraded soil surface moderated soil surface temperatures; daytime temperatures were cooler and night-time temperatures were warmer compared to areas with no branches. The above treatments facilitate the establishment of soil fauna and vegetation that further increases biotic control over hydrologic and nutrient cycling processes (Whisenant *et al.* 1995; Ludwig & Tongway 1996; Tongway & Ludwig 1996).

In conclusion, livestock grazing in *E. salmonophloia* woodlands changes conditions and disrupts ecosystem processes resulting in the external loss of scarce resources from within remnants. These observations confirm Yates and Hobbs (1997a) suggestion that many remnant *E. salmonophloia* woodlands may have crossed thresholds whereby the removal of livestock alone will not lead to their recovery. Restoration will require strategies that capture resources, increase their retention, and improve microclimate in remnants.

ACKNOWLEDGEMENTS

We thank Lynn Atkins for assistance with fieldwork and Sue Yates for critical comments on the manuscript.

REFERENCES

Abensperg-Traun M., Smith G. T., Arnold G. W. & Steven D. E. (1996) The effects of habitat fragmentation on animal communities in remnants of gimlet *Eucalyptus salubris* woodland in the Western Australian wheatbelt. 1. Arthropods. *J. Appl. Ecol.* **33,** 1281–301.

Adamson D. A. & Fox M. D. (1982) Change in Australasian vegetation since European settlement. In: *A History of Australasian Vegetation* (ed. J. M. B. Smith) pp. 109–46. McGraw-Hill, Sydney.

Braunack M. V. & Walker J. (1985) Recovery of some surface soil properties of ecological interest after sheep grazing in a semi-arid woodland. *Aust. J. Ecol.* **10,** 451–60.

Cale P. & Hobbs R. J. (1991) Condition of roadside vegetation in relation to nutrient status. In: *Nature Conservation 2: the Role of Corridors* (eds D. A. Saunders & R. J. Hobbs) pp. 353–62. Surrey Beatty and Sons, Chipping Norton.

Eldridge D. J. & Koen T. B. (1993) Run-off and sediment yield from a semi-arid woodland in eastern Australia. II. Variation in some soil hydrological properties along a gradient in soil surface condition. *Rangel. J.* **15,** 234–46.

Goldney D., Bauer J., Bryant H., Hodgkins D. & Watson G. (1995) Winning battles but losing the war: the education marketing imperative. In: *Nature Conservation 4: the Role of Networks* (eds D. A. Saunders, J. Craig & L. Mattiske) pp. 547–88. Surrey Beatty & Sons, Chipping Norton, NSW.

Goldney D. C. & Bowie J. S. (1990) Some management implications for the conservation of vegetation remnants and associated fauna in the central western region of New South Wales. *Proc. Ecol. Soc. Aust.* **16,** 427–40.

Graetz R. D. & Tongway D. J. (1986) Influence of grazing management on vegetation, soil structure and nutrient distribution and the infiltration of applied rainfall in a semi-arid chenopod shrubland. *Aust. J. Ecol.* **11,** 347–60.

Green R. H. (1993) Application of repeated measures designs in environmental impact and monitoring studies. *Aust. J. Ecol.* **18,** 81–98.

Greene R. S. B. (1992) Soil physical properties of three geomorphic zones in a semi-arid mulga woodland. *Aust. J. Soil Res.* **30,** 55–69.

Greene R. S. B. & Tongway D. J. (1989) The significance of (surface) physical and chemical properties in determining soil surface condition of red earths in rangelands. *Aust. J. Soil Res.* **27,** 213–25.

Hamblin A. P. (1984) The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol. *Soil Tillage Res.* **4,** 543–59.

Howling G. (1996) *Temperate Woodlands: Their Conservation Status in Australia*. WWF Australia, Sydney.

Kirkpatrick J. & Gilfedder L. (1995) Maintaining integrity compared with maintaining rare and threatened taxa in remnant bushland in subhumid Tasmania. *Biol. Conserv.* **74,** 1–8.

Lantzke N. (1992) *Soils of the Northam Advisory District*, 1 *The Zone of Ancient Drainage*. Department of Agriculture, Western Australia.

Ludwig J. A. & Tongway D. J. (1995) Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. *Landscape Ecol.* **10,** 51–63.

Ludwig J. A. & Tongway D. J. (1996) Rehabilitation of semiarid landscapes in Australia. 2. Restoring vegetation patches. *Restor. Ecol.* **4,** 398–406.

Ludwig J. A., Tongway D. J. & Marsden S. G. (1994) A flow filter model for simulating the conservation of limited resources in spatially heterogeneous, semi-arid landscapes. *Pac. Conserv. Biol.* **1,** 209–13.

Ludwig J. A., Tongway D. J., Freudenberger D., Noble J. & Hogkinson K. (1997) *Landscape Ecology, Function and Management Principles from Australia's Rangelands*. CSIRO Australia, Melbourne.

Lunt I. D. (1991) Management of remnant lowland grasslands and grassy woodlands for nature conservation: a review. *Vic. Natur.* **108,** 57–66.

McArthur W. M. (1991) *Reference Soils of South-Western Australia*. Department of Agriculture, Western Australia, Perth.

McIntyre S. & Lavorel S. (1994) How environmental and disturbance factors influence species composition in temperate Australian grasslands. *J. Veg. Sci.* **5,** 373–84.

Main B. Y. (1992) Social history and impact on landscape (with Trayning: case history of a shire by D. Couper). In: *Reintegrating Fragmented Landscapes Towards Sustainable Production and Nature Conservation* (eds R. J. Hobbs & D. A. Saunders) pp. 23–65. Springer-Verlag, New York.

Moore R. M. (1970) South-eastern temperate woodlands and grasslands. In: *Australian Grasslands* (ed. R. M. Moore) pp. 169–90. Australian National University Press, Canberra.

Nulsen R. A. (1992) Changes in soil properties. In: *Reintegrating*

Fragmented Landscapes Towards Sustainable Production and Nature Conservation (eds R. J. Hobbs & D. A. Saunders) pp. 107–45. Springer-Verlag, New York.

Perroux K. M. & White I. (1988) Designs for disk permeameters. *Soil Sci. Soc. Am. J.* **52,** 1205–15.

Petit N. E., Froend R. H. & Ladd P. G. (1995) Grazing in remnant woodland vegetation: changes in species composition and life form groups. *J. Veg. Sci.* **6,** 121–30.

Prober S. M. (1996) Conservation of grassy white box woodlands: rangewide floristic variation and implications for reserve design. *Aust. J. Bot.* **44,** 57–77.

Prober S. M. & Thiele K. R. (1993) The ecology and genetics of remnant grassy white box woodlands in relation to their conservation. *Vic. Natur.* **110,** 30–6.

Prober S. M. & Thiele K. R. (1995) Conservation of the grassy white box Woodlands: Contributions of size and disturbance to floristic composition and diversity of remnants. *Aust. J. Bot.* **43,** 349–66.

Proffitt A. P. B., Bendotti S., Howell M. R. & Eastham J. (1993) The effect of sheep trampling and grazing on soil physical properties and pasture growth for a red brown earth. *Aust. J. Agric. Res.* **44,** 317–31.

Robinson D. & Traill B. (1996) Conserving woodland birds in the wheat and sheep belts of southern Australia. *RAOU Conservation Statement* **10** (Supplement to *Wingspan* 6).

Scougall S. A., Majer J. D. & Hobbs R. J. (1993) Edge effects in grazed and ungrazed Western Australian wheatbelt remnants in relation to ecosystem reconstruction. In: *Nature Conservation 3: Reconstruction of Fragmented Ecosystems, Global and Regional Perspectives* (eds D. A. Saunders, R. J. Hobbs & P. R. Ehrlich) pp. 163–78. Surrey Beatty and Sons, Chipping Norton, New South Wales.

Sivertsen D. (1993) Conservation of remnant vegetation in the box and ironbark lands of New South Wales. *Vic. Natur.* **110,** 24–9.

Tisdall J. M. & Oades J. M. (1982) Organic matter and water-stable aggregates in soils. *J. Soil Sci.* **33,** 141–63.

Tongway D. J. (1991) Functional analysis of degraded rangelands as a means of defining appropriate restoration techniques. In: *Proceedings of Fourth International Rangeland Congress, Association Francaise de Pastoralisme* (eds A. Gaston, M. Kerrick & H. Le Houerou) pp. 166–8. Offset 2000, Montpellier, France.

Tongway D. J. (1994). *Rangeland Soil Condition Assessment Manual.* CSIRO, Melbourne, Australia, Canberra.

Tongway D. J. & Ludwig J. A. (1990) Vegetation and soil patterning in the semi arid mulga lands of Eastern Australia. *Aust. J. Ecol.* **15,** 23–34.

Tongway D. J. & Ludwig J. A. (1993) Rehabilitation of mine sites and pastoral lands: the ecosystem function approach. In: *Proceedings of the Goldfields International Conference on Arid Landcare* (ed. M. di Russo) pp. 51–7. Mileno di Russo, Hamilton Hill, Western Australia.

Tongway D. J. & Ludwig J. A. (1994) Small-scale resource heterogeneity in semi-arid landscapes. *Pac. Conserv. Biol.* **1,** 201–8.

Tongway D. J. & Ludwig J. A. (1996) Rehabilitation of semiarid landscapes in Australia. 1. Restoring Productive Soil Patches. *Restor. Ecol.* **4,** 388–97.

Tremont R. M. & McIntyre S. (1994) Natural grassy vegetation and native forbs in temperate Australia: structure, dynamics and life histories. *Aust. J. Bot.* **42,** 641–58.

Whisenant S. G., Thurow T. L. & Maranz S. J. (1995) Initiating autogenic restoration on shallow semi-arid sites. *Restor. Ecol.* **3,** 61–7.

Willatt S. T. & Pullar D. M. (1983) Changes in soil physical properties under grazed pastures. *Aust. J. Soil Res.* **22,** 343–8.

Wilson A. D. (1990) The effect of grazing on Australian ecosystems. *Proc. Ecol. Soc. Aust.* **16,** 235–44.

Yates C. J. (1995) Factors Limiting the Recruitment of *Eucalyptus salmonophloia* F. Muell. (salmon gum). PhD Thesis, Murdoch University, Perth, Western Australia.

Yates C. J. & Hobbs R. J. (1997a) Temperate eucalypt woodlands: a review of their status, processes threatening their persistence and techniques for restoration. *Aust. J. Bot.* **45,** 949–73.

Yates C. J. & Hobbs R. J. (1997b) Woodland restoration in the Western Australian Wheatbelt. A conceptual framework using a state and transition model. *Rest. Ecol.* **5,** 28–35.