Rehabilitation of Semiarid Landscapes in Australia. I. Restoring Productive Soil Patches

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Abstract

A rehabilitation procedure designed to reestablish resource control processes in a degraded *Acacia aneura* woodland was successful in improving soil nitrogen and carbon content, exchange properties, and water infiltration rates. Soil respiration rates and soil fauna populations increased, and soil temperatures were moderated. The procedure comprised laying piles of branches in patches on the contour of bare, gently sloping landscapes, with the expectation that soil, water, and litter would accumulate in these branch piles, thus improving the soil habitat and its productive potential. The procedure was derived from landscape function analysis, indicating that surface water flow was the principal means of resource transfer in these landscapes. Under degradation such overland flow results in a loss of resources. This rehabilitation procedure reversed loss processes, resulting in gains in the productive potential of soils within patches. This procedure was successful despite grazing pressure being maintained throughout the experiment.

Introduction

Pastoral settlement in Australian semiarid lands has a relatively short history of about 120–150 years (Noble & Tongway 1986). Evidence of degradation became clear only two decades after settlement (Reid 1876; Dixon 1892; Anonymous 1901). This degradation was due to a number of factors: lack of appreciation of the innate unreliability of rainfall, substantial decrease in fire frequency, the advent of large numbers of feral grazers such as rabbits and goats, and an increase in native herbivores such as kangaroos due to improved water supplies. These impacts were compounded by the slow means of moving livestock into and out of properties, with droving (moving livestock by foot) being the only means of redistributing stock numbers in the early days.

Degradation within semiarid regions is a continuing issue, especially during prolonged droughts when the country has very little vegetation cover and grazing animals break up the soil surface, making it more erodable. Among the long-term effects of degradation are: (1) losses of palatable perennial grasses; (2) gains in inedible native shrubs and ephemerals; and (3) soil erosion (Condon et al. 1969; Harrington et al. 1984)

In the past, attempts to deal with perceived soil degradation were based on mechanical treatments aimed at increasing infiltration of water into the soil (Cunningham 1967; Green 1989; Hacker 1989). These treatments had limited success because they were: (1) imported from farming regions with higher and more reliable rainfall—by the time favorable seasonal conditions arrived the treatments had failed; (2) often used on dispersing soils that slumped after the first rain, rendering the treatment ineffective; (3) often creating more disturbance, initiating another round of soil erosion; and (4) often promoting inedible shrub increase. In addition, mechanical treatments were too expensive for the extensive and marginal pastoral enterprises they were meant to help.

Attempts to rehabilitate the semi-arid woodlands by reseeding bare areas with grasses, usually exotics, have largely failed (Noble et al. 1984). Soils in the semi arid woodlands are mostly infertile, acidic red earths (Stace et al. 1968; Webb et al. 1980). Perennial grasses introduced from overseas generally come from areas with more fertile soils with neutral pH (e.g., *Cenchris ciliaris* from Africa requires over 25 ppm of available phosphorus to thrive; Christie 1975).

Reseeding is often done in combination with various mechanical soil reclamation treatments aimed at erosion control including pitting, ripping, furrowing, blade ploughing, and blading to form contour and ponding banks (Noble et al. 1984; Green 1989; Hacker 1989). These treatments have been successful only in reclaiming some local areas under favorable climatic conditions. The reasons why some treatments succeeded and others failed were seldom investigated by rigorous analysis (M. Friedel, personal communication). The expectation was that colonizing plants would create a favorable soil microhabitat *de novo*, from highly eroded and unstable soils. Part of the problem was that the solutions sought were too simplistic; water infiltration was the only perceived problem, little attention was paid to factors such as nutrient status and cycling.

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Recent basic studies that have linked terrain, soil, and plant patterns to landscape processes have given rise to generic models of semiarid landscape function (Tongway & Ludwig 1990; Tongway 1991; Ludwig & Tongway 1993, 1995). By definition, water and soil nutrients are in short supply in arid and semiarid lands (Noy-Meir 1973). When undegraded, these lands have a high diversity of perennial plants occurring in natural patches (Tongway & Ludwig 1994). These patches capture and store water and nutrients, and then slowly release these resources so that the perennial plants that comprise the patches survive over long time spans. It is important to understand the processes by which patches are maintained in a landscape. Thus, efficient landscape functioning depends on patches capturing water and nutrients, which are limited in these semiarid environments (Noy-Meir 1981, 1985).

We propose that if landscape function can be adequately defined in terms of pattern, and the processes that determine that pattern, then dysfunction or degradation can be addressed objectively by identifying the landscape processes that have been diminished (Tongway 1991). This landscape-function hypothesis can be tested by improving the processes suspected to be ineffective in degraded lands.

We test our understanding of landscape function in semiarid woodlands by attempting to rehabilitate a degraded semiarid landscape similar to those patchy systems described by Tongway and Ludwig (1990) and Ludwig and Tongway (1995). Our aim was to reinstate landscape processes on degraded bare slopes by constructing piles of branches that were expected to obstruct water flow and create aerodynamic drag. The hypothesis was that these obstructions would filter out or capture resources entrained in water flows or wind, thus creating resource-rich or fertile patches and restoring the natural patchiness of these landscapes.

Our experimental approach was to observe edaphic and vegetative responses over time after constructing branch piles. The expectation was that as the experimental plots with branches become richer in resources, the soil would improve its habitat value and, hence, support increased microbial, invertebrate, and plant populations characteristic of these landscapes when undegraded. We describe soil habitat improvements in terms of microtopographic, microenvironmental soil fertility and infiltration properties. Plant responses are described in a companion paper (Ludwig & Tongway 1996).

Methods

Study Site

The study was conducted within a 200 ha grazing trial site of the Commonwealth Scientific and Industrial Research Organization (CSIRO) located on a property called Lake Mere occurring in the center of the semiarid woodlands of eastern Australia (Fig. 1). Rainfall averages 290 mm and is aseasonally distributed, although winter rains are generally more effective due to cooler temperatures and lower evaporation rates (Harrington et al. 1984). The soils are acidic red earths (Stace et al. 1968) and are comprised of red, fine-sandy clay loams derived from siliceous parent materials and are known locally as "hard red earths" (Walker 1991). These soils are characteristically infertile (Webb et al. 1980), but there are zones of varying fertility as indicated above. In particular, levels of phosphorous are very low (Wilson et al. 1988).

The Lake Mere landscape consists of undulating stony ridges and slopes extending into weakly dendritic drainage lines (Walker 1991). This landscape is typical of extensive areas within the semiarid woodlands (Tongway & Ludwig 1990; Ludwig & Tongway 1995), where the vegetation is dominated by *Acacia aneura* F. Muell. ex Benth (mulga) organized into groves and treeless intergroves (Fig. 2). The study site was carefully selected to be representative of this landscape, although since European settlement much of this vegetation has changed from open, grassy, *Acacia aneura* woodland to more closed shrubby woodland (Harrington et al. 1984).

Experimental Design

Within the 200 ha Lake Mere grazing trial of 13 paddocks, 2 paddocks (B & M) were selected for this landscape rehabilitation experiment, which we established in

Figure 1. Location of the experimental study site (●) on Lake Mere in the semiarid woodlands of eastern Australia (stippled area).

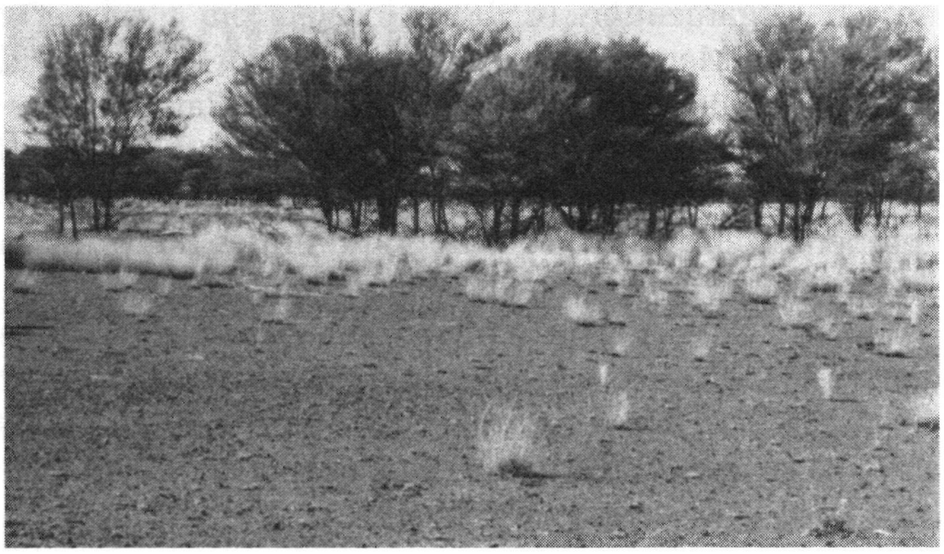

Figure 2. Down-slope view of a typical semiarid woodland landscape at Lake Mere, where a grove of mulga trees (background) growing on the contour is separated by an open runoff slope (foreground).

August 1988. Paddock B was being grazed by both sheep and kangaroos at an intensity equivalent to 0.7 sheep per ha (sheep are dry or non-lactating, and one kangaroo equals two-thirds of a dry sheep). In terms of land area, this is the equivalent of 3.5 acres per dry sheep. Paddock M was substantially ungrazed by domestic stock and feral or native animals, except on rare occasions of short duration when sheep were being transferred between paddocks.

Runoff slopes in each paddock were surveyed for elevation contours, and eight transects 54 m long, positioned along the contour, were fitted into the available space with at least a 10 m separation between transects down the slope. Five transects were selected at random from this set of eight. Eight plots 2×5 m were located longitudinally along each transect, with a 2 m buffer zone between each plot. Each plot was permanently marked with steel and wooden pegs, and two steel benchmark pegs were installed 0.8 m deep at the ends of every transect.

Eight combinations of the following three treatments were randomly applied to the eight plots on each transect (Fig. 3): (1) with and without a pile of branches; (2) with and without nutrients; and (3) with and without organic matter. We constructed the piles of branches with locally available *Acacia aneura* trees, stacking the branches about 0.5 m high, ensuring that the main stems were in contact with the soil over each plot with this treatment (Fig. 4). Nutrients were supplied as a mixture of single superphosphate (1 g P m^{-2}) and ammonium sulphate (10 g N m^{-2}) added each autumn for a total of three applications. Organic matter was added as litter once (at the start of the experiment) at a rate of 1 kg dw m^{-2} in the form of *Acacia aneura* leaf mulch harvested from nearby *Acacia aneura* groves. Data obtained from this complete, fully factorial, randomized design lend themselves to rigorous statistical analyses.

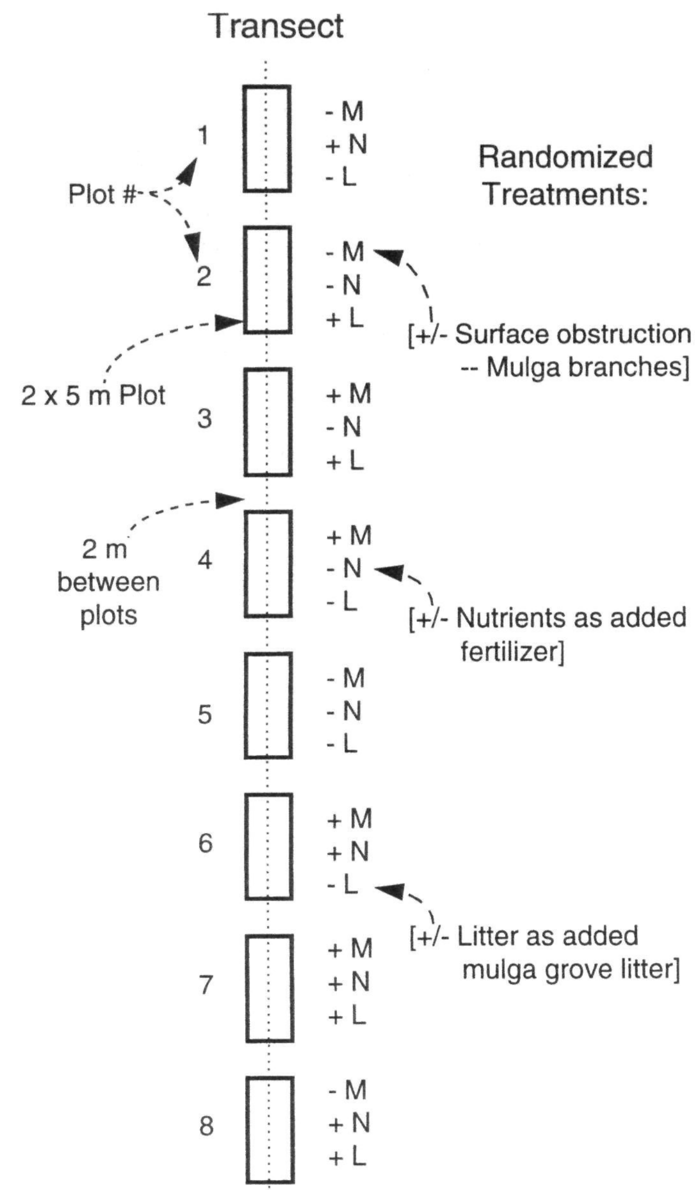

Figure 3. A schematic of a typical treatment transect showing the full factorial random application of three treatments to eight 2×5–m plots positioned in a line across the slope. The application of treatments to plots was rerandomized for each of the five transects in the grazed and ungrazed paddocks, Lake Mere, New South Wales.

Field Measurements

Prior to the application of the treatments, soil samples were taken from each plot by bulking five representative cores divided into depth intervals of 0–1, 1–3, 3–5, and 5–10 cm. The soil was air-dried, crushed to pass a 2-mm screen, and stored in air-tight containers until analyzed. The soil samples were analyzed by the following techniques: (1) electrical conductivity, 1:5 soil in water (Loveday 1974); (2) pH, 1:5 soil in 0.01M $CaCl_2$; (3) organic carbon by a modified Walkley Black technique (Colwell 1969); (4) organic nitrogen (Twine & Williams 1967); (5) available phosphorous (Colwell 1965); (6) exchangeable cations and cation-exchange capacity (CEC) (Chhabra et al. 1975); and (7) potentially available nitrogen (Gianello & Bremner 1986).

In order to assess loss or gain in soil over the period of the trial, plot levels were carefully measured to a precision of 1 mm with a surveyors level. Each plot was divided into ten rows 50 cm apart. Levels were read at 40-cm intervals on each row (50 readings per plot). These

Figure 4. View of an experimental pile of branches forming a 2 × 5–m treatment plot on which observations were taken.

were carefully registered with the permanent bench marks installed at the ends of each transect.

The density and foliage cover of all perennial plants was observed in ten 1 × 1 m quadrats within each 2 × 5 m plot. Pre-treatment observations were made in the winter of 1988 and every three months (season) for three years. The results from these measurements are reported and discussed in a companion paper (Ludwig & Tongway 1996).

After the trial had run for three years (September 1988 to September 1991) the following measurements were recorded: (1) soil levels on each plot were repeated to estimate erosion and deposition processes; (2) soil was resampled and analyzed for nutrient content from each plot by the same procedure as at the start; (3) water infiltration rates were made with a disk permeameter (Perroux & White 1988) on randomly selected transects in each paddock; and (4) soil respiration was measured by an inverted-box alkali-absorption method (Hartigan 1980; Tongway & Hodgkinson 1992). CO_2 evolved over a period of 24-hr was calculated.

Once-off measurements included (1) air versus soil surface temperatures at 3 hourly intervals for 24 hours on the grazed paddock in October 1989 taken with a calibrated thermocouple; and (2) ant numbers counted on the grazed paddock after the trial had been operating for 18 months (April 1990)—numbers of ants in each of ten 1-m^2 quadrats per plot on every treatment combination recorded at 0700 and 1600 hours.

Data Analysis

Soil nutrient results were subjected to analysis of variance to examine the net effect of the treatments over the 3 year period from September 1988 to September 1991. Tukey's HSD test was used to evaluate significant differences.

Results

In the grazed paddock over the 3 year period of the experiment, branch treatment plots, compared to plots with no branches, had significant increases in the concentration of organic nitrogen, organic carbon, CEC and exchangeable potassium and calcium in the surface layer of soil (Table 1a). Added fertilizer and litter treatments had no statistically significant effects, so those comparisons are not shown. The results are similar, for the ungrazed paddock except that the 1991 values were significantly higher than the 1988 values for organic nitrogen and carbon, available phosphorus and exchangeable potassium, whether branches were in place or not (Table lb). There were statistically significant increases in electrical conductivity, but the ecological consequences are negligible because of the very low values involved.

Branch-treated plots gained soil significantly over the 3 year period, whereas plots with no branches lost soil (Table 2). The grazed paddock both gained more soil on the branch-treated plots and lost more from the plots with no branches than did the ungrazed paddock. Treatments of added nutrients and litter had no effect on soil accumulation or loss. The accumulation of soil and litter materials was greatest on the up-slope side of the plots with branches, with some erosion of soil off the down-slope edge (Fig. 5). The surface of the plots with no branches eroded fairly uniformly.

The branch-treated plots in both paddocks had significantly higher infiltration rates than the control, nutrient-alone, and litter-alone plots, though the increase was less (about half) on the ungrazed paddock (Table 2). Because there were no significant differences in water infiltration rates between control plots and litter-only and nutrient-only plots, all plots with branches, whether with or without litter or nutrient treatments, were statistically compared to all the plots with no branches.

The branch-treatment plots in the grazed paddock had higher values for soil respiration than the plots with no branches (Table 2). In the ungrazed paddock, there were no significant differences in soil respiration between treatments with branches and with no branches.

The branch-treatment plots had cooler soil temperatures at a depth of 1 cm during the day and warmer temperatures during the night than did the open plots with no branches (Fig. 6). Thus soil temperatures were less extreme within branch plots and more closely tracked air temperatures above the plot than did the plots without branches.

Ants were significantly more numerous on the branch-treated plots (Table 3). The number of ants was not significantly different in the morning and afternoon counts, nor between any treatments other than with and without branches.

Table 1. Mean soil nutrient or indicator values for 1988 and 1991 in branch and no-branch treatment plots, respectively.*

(a) Grazed Paddock

		Branches		*No Branches*	
Soil Indicator	*Depth (cm)*	*1988*	*1991*	*1988*	*1991*
Organic Nitrogen (%)	0–1	0.066^{a}	0.103^{b}	0.062^{a}	0.074^{a}
	1–3	0.050^{a}	0.052^{a}	0.044^{a}	0.043$^{\beta}$
	3–5	0.045^{a}	0.042^{a}	0.045a	0.037^{a}
	5–10	0.044^{a}	0.040^{a}	0.041^{a}	0.035^{a}
Available Nitrogen (ppm)	0–1	5.9^{a}	8.1^{a}	6.3^{a}	4.4^{a}
	1–3	3.9^{a}	3.9^{a}	3.9^{b}	1.9^{a}
	3–5	3.5^{b}	2.1^{a}	3.5^{b}	1.6^{a}
	5–10	3.0^{b}	1.7^{a}	3.1^{b}	1.1^{a}
Organic Carbon (%)	0–1	0.73^{a}	1.00^{b}	0.60^{a}	0.71^{a}
	1–3	0.61^{a}	0.60^{a}	0.55^{a}	0.53^{a}
	3–5	0.59^{a}	0.53^{a}	0.49^{a}	0.46^{a}
	5–10	0.55^{a}	0.50^{a}	0.48^{a}	0.44^{a}
Available Phosphorus (ppm)	0–1	15.8^{a}	16.5^{a}	14.9^{a}	17.1^{a}
	1–3	6.5^{a}	8.8^{a}	6.3^{a}	8.4^{a}
	3–5	3.0^{a}	4.8^{b}	3.1^{a}	4.5^{a}
	5–10	2.9^{a}	3.1^{a}	3.0^{a}	2.8^{a}
CEC (mmol kg^{-1})	0–1	8.65^{a}	10.48^{b}	8.85^{a}	9.78^{a}
	1–3	8.33^{a}	9.46^{b}	8.45^{a}	8.46^{a}
	3–5	8.26^{a}	9.03^{b}	8.57^{a}	8.88^{a}
	5–10	8.28^{a}	9.27^{b}	8.58^{a}	9.06^{a}
K^{+} (mmol kg^{-1})	0–1	1.32^{a}	2.16^{b}	1.38^{a}	1.70^{a}
	1–3	1.16^{a}	1.58^{b}	1.29^{a}	1.43^{a}
	3–5	1.08^{a}	1.32^{a}	1.19^{a}	1.29^{a}
	5–10	1.04^{a}	1.16^{a}	1.09^{a}	1.17^{a}
Mg^{++} (mmol kg^{-1})	0–1	1.37^{a}	1.42^{a}	1.54^{a}	1.60^{a}
	1–3	1.01^{a}	1.16^{a}	1.20^{a}	1.22^{a}
	3–5	0.77^{a}	0.91^{a}	0.97^{a}	0.96^{a}
	5–10	0.67^{a}	0.75^{a}	0.80^{a}	0.79^{a}
Ca^{++} (mmol kg^{-1})	0–1	2.23^{a}	2.88^{b}	2.57^{a}	2.78^{a}
	1–3	1.97^{a}	2.35^{a}	2.45^{a}	2.52^{a}
	3–5	1.74^{a}	2.08^{a}	2.35^{a}	2.45^{a}
	5–10	1.74^{a}	1.95^{a}	2.30^{a}	2.35^{a}
pH (0.01 m $CaCl_2$)	0–1	4.67^{a}	5.10^{b}	4.82^{a}	5.10^{a}
	1–3	4.26^{a}	4.43^{a}	4.50^{a}	4.58^{a}
	3–5	4.01^{a}	4.20^{a}	4.18^{a}	4.29^{a}
	5–10	3.91^{a}	4.08^{a}	4.02^{a}	4.15^{a}
Electrical Conductivity (μS_{Δ} cm^{-1})	0–1	14^{a}	64^{b}	16^{a}	22^{b}
	1–3	12^{a}	61^{b}	14^{a}	25^{b}
	3–5	17^{a}	30^{b}	21^{a}	28^{a}
	5–10	25^{a}	27^{a}	26^{a}	32^{a}
(b) Ungrazed Paddock					
Organic Nitrogen (%)	0–1	0.058^{a}	0.092^{b}	0.058^{a}	0.086^{b}
	1–3	0.041^{a}	0.047^{a}	0.045^{a}	0.045^{a}
	3–5	0.042^{a}	0.036^{a}	0.039^{a}	0.039^{a}
	5–10	0.039^{a}	0.037^{a}	0.036^{a}	0.034^{a}
Available Nitrogen (ppm)	0–1	5.5^{a}	6.9^{a}	5.9^{a}	5.7^{a}
	1–3	3.4^{a}	3.4^{a}	4.5^{a}	2.9^{a}
	3–5	3.3^{a}	2.3^{a}	3.8^{b}	2.3^{a}
	5–10	3.3^{b}	1.9^{a}	3.6^{b}	1.7^{a}
Organic Carbon (%)	0–1	0.58^{a}	0.99^{b}	0.61^{a}	0.87^{b}
	1–3	0.49^{a}	0.65^{b}	0.52^{a}	0.65^{b}
	3–5	0.48^{a}	0.55^{a}	0.48^{a}	0.66^{a}
	5–10	0.48^{a}	0.48^{a}	0.44^{a}	0.51^{a}
Available Phosphorus (ppm)	0–1	9.9^{a}	14.5^{b}	8.9^{a}	15.3^{b}
	1–3	4.4^{a}	7.1^{b}	5.6^{a}	8.1^{a}
	3–5	2.1^{a}	4^{b}	2.7^{a}	4.5^{b}
	5–10	2.6^{a}	2.7^{a}	2.6^{a}	3.0^{a}

Table 1 continued

(b) Ungrazed Paddock

Soil Indicator	*Depth (cm)*	*Branches* 1988	*Branches* 1991	*No Branches* 1988	*No Branches* 1991
CEC (mmol kg^{-1})	0–1	8.82^{a}	10.11^{b}	8.82^{a}	10.03^{a}
	1–3	8.59^{a}	8.92^{a}	9.06^{a}	9.45^{a}
	3–5	8.30^{a}	9.61^{a}	9.07^{a}	9.61^{a}
	5–10	9.26^{a}	9.38^{a}	9.1^{a}	9.65^{a}
K^{+} (mmol kg^{-1})	0–1	1.23^{a}	1.69^{b}	1.33^{a}	1.51^{b}
	1–3	1.18^{a}	1.49^{b}	1.28^{a}	1.39^{a}
	3–5	1.15^{a}	1.28^{a}	1.24^{a}	1.27^{a}
	5–10	1.07^{a}	1.12^{a}	1.10^{a}	1.16^{a}
Mg^{++} (mmol kg^{-1})	0–1	1.52^{a}	1.67^{b}	1.75^{a}	1.79^{a}
	1–3	1.13^{a}	1.33^{a}	1.49^{a}	1.48^{a}
	3–5	1.05^{a}	1.08^{a}	1.33^{a}	1.26^{a}
	5–10	0.96^{a}	.095^{a}	1.22^{a}	1.19^{a}
Ca^{++} (mmol kg^{-1})	0–1	2.28^{a}	2.88^{b}	2.61^{a}	2.78^{a}
	1–3	2.18^{a}	2.46^{a}	2.65^{a}	2.73^{a}
	3–5	2.13^{a}	2.27^{a}	2.63^{a}	2.62^{a}
	5–10	2.19^{a}	2.25^{a}	2.67^{a}	2.68^{a}
pH (0.01 m $CaCl_2$)	0–1	4.73^{a}	5.02^{b}	4.97^{a}	5.26^{a}
	1–3	4.38^{a}	4.58^{a}	4.70^{a}	4.84^{a}
	3–5	4.17^{a}	4.29^{a}	4.50^{a}	4.54^{a}
	5–10	4.06^{a}	4.21^{a}	4.41^{a}	4.49^{a}
Electrical Conductivity (μS_{Δ} cm^{-1})	0–1	15^{a}	46^{b}	17^{a}	25^{b}
	1–3	13^{a}	51^{b}	12^{a}	36^{b}
	3–5	15^{a}	31^{b}	14^{a}	28^{b}
	5–10	20^{a}	24^{a}	17^{a}	28^{b}

*For each pair of years within a treatment for each soil depth and indicator, means with different superscript letters (a < b) are significantly different ($p < 0.05$; df = 8), based on Tukey's HSD test.

Discussion

As a rehabilitation treatment on bare slopes, the branch piles had a dramatic effect on soil deposition and erosion, with clear gains of soil on the treated plots compared to plots with no branches, which lost on average about 0.85 mm per year. The branch treatments in the grazed paddock experienced greater gains than those in the ungrazed paddock (0.6 versus 0.5 mm per year), as well as greater losses with no branches (0.9 versus 0.8 mm per year). This is because persistent hoof action creates a greater amount of material, which is then available for transport. The grazed paddock also had a smaller number of resource traps (e.g., grass clumps, log-mounds; Tongway & Ludwig 1994) than the ungrazed paddock.

The erosion recorded across both paddocks of 0.85 mm per year is higher than reported by Johns (1983) for a similar landscape type, where there were losses of only 0.055 mm per year. Johns used a subsample of sediment yield from constructed runoff plots to calculate these losses. The reason for this large discrepancy is not clear, but it could be due to the extremely degraded state of the landscapes Johns studied, where the soil surface was already reduced to a layer of relatively resistant material. The results reported here are based on

Table 2. Soil elevation changes between September 1988 and September 1991 and water infiltration and soil respiration rates for September 1991 in treated and untreated plots, Lake Mere, New South Wales.*

Soil Property	*Grazed Paddock* Branches	*Grazed Paddock* No Branches	*Ungrazed Paddock* Branches	*Ungrazed Paddock* No Branches
Soil Elevation (mm ± SE)	+1.9 ± 0.6^{b}	−2.7 ± 0.5^{a}	+1.5 ± 0.7^{b}	−2.4 ± 0.6^{a}
Water Infiltration (mm $hour^{-1}$ ± SE)	117.9 ± 23.2^{b}	11.6 ± 0.1^{a}	55.7 ± 2.1^{b}	24.1 ± 0.9^{a}
Soil Respiration (mg CO_2 m^{-2} $hour^{-1}$ ± SE)	221.4 ± 18.0^{b}	151.4 ± 12.4^{a}	140.3 ± 10.6^{a}	128.7 ± 10.9^{a}

*For each soil property, means within paddocks that have different superscripts are significantly different ($p < 0.01$, n = 20). Significance of means between paddocks was not tested because paddocks are unreplicated.

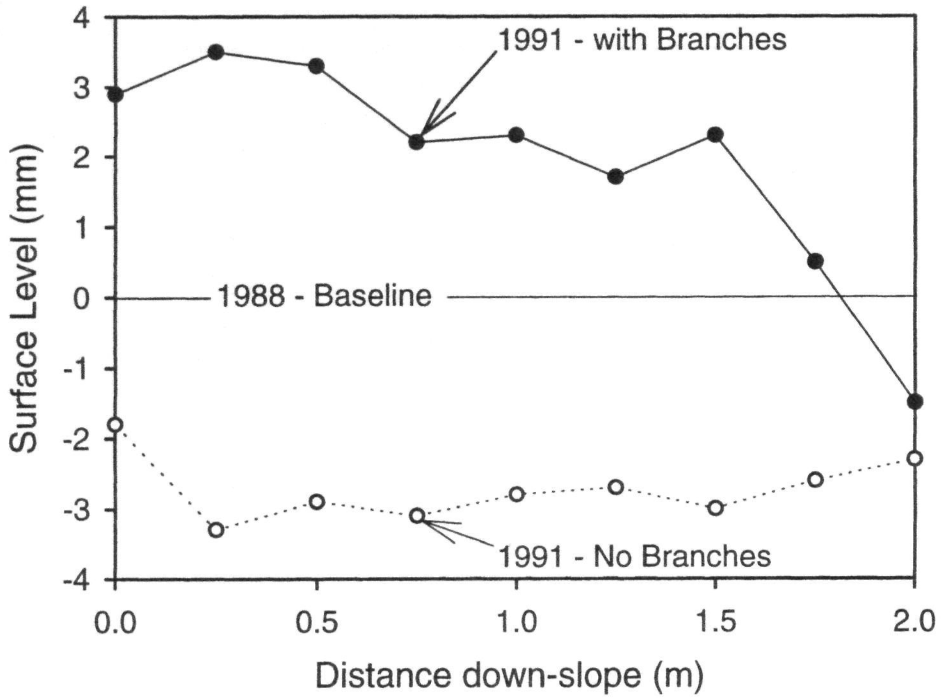

Figure 5. Mean down-slope soil surface levels for 1988 and 1991 on plots treated with branches and on plots with no branches, grazed paddock, Lake Mere, New South Wales. The zero change line is in reference to 1988 surface levels. Zero distance is the upslope edge of the 2 × 5–m plots.

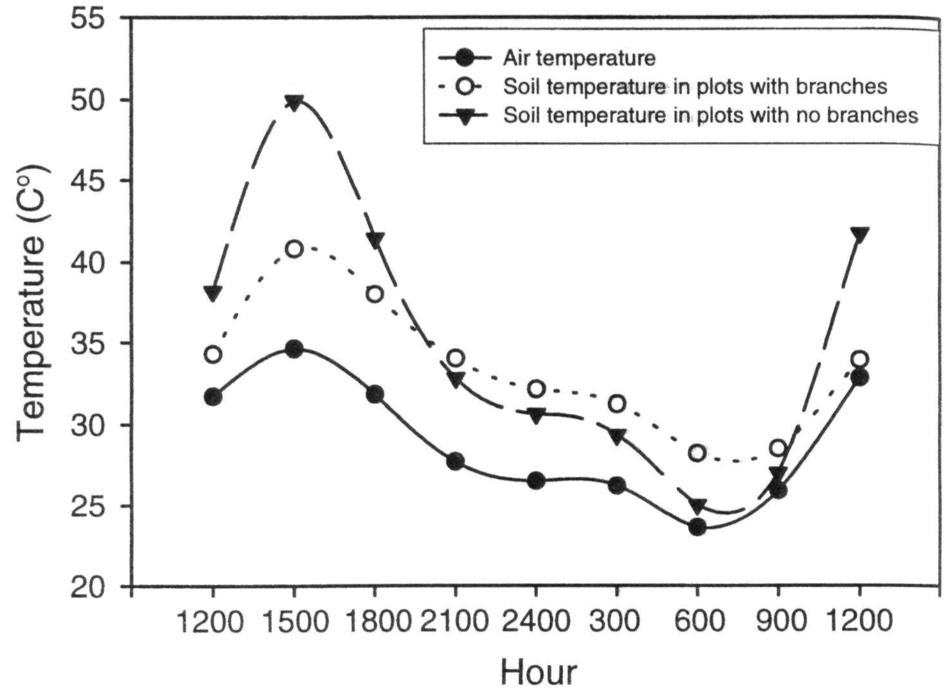

Figure 6. Mean air and soil surface temperatures on plots with branches and with no branches, Lake Mere, New South Wales. Observations were made at 3-hour intervals over a 24-hour period starting at noon on clear days in mid-spring (October 1989).

direct survey measurements in reference to fixed benchmarks, and our rates also reflect the initial undegraded state of the landscape studied.

The origin of the accumulated soil in the treated plots was both fluvial and aeolian. Personal observations on windy days confirmed that both suspended and saltating soil particles lodged in the branches due to turbulence and drag created by the piles. The branches caused particles to drop out of the airflow into the relatively protected area of branches, and the capacity of these particles to be remobilized was greatly reduced. Litter fragments from trees such as *Eucalyptus populnea* (poplar box), occurring at least 100 m away, were found in the branch piles, indicating an aeolian litter input. Fluvial processes were also clearly active, trains or rafts of leaf litter and dung were observed after runoff events on the upslope edge of the plots with branches, and the upslope edge of plots accumulated more soil than the downslope edge (Fig. 5).

The branch treatment increased water infiltration markedly. The branch plots achieved a 10-fold increase in infiltration rate on the grazed paddock in three years, up to a level of about half that of a mature, long-extant *Acacia aneura* grove (Tongway et al. 1989; Tongway & Ludwig 1990; Greene 1992). The size of this change in soil infiltration rate was unexpected. This effect was more pronounced in the grazed paddock than in the ungrazed. The magnitude of this amelioration effect means that significantly more rain can infiltrate into these landscape patches than into the surrounding landscapes, so less rainfall will run out of the landscape into creeks, rivers and lakes (Ludwig & Marsden 1995).

Rainfall rates rarely exceed 100 mm per hour in these semi-arid environments. For example, this rate was exceeded, over 6 minute periods, on only three occasions between 1963 and 1982 (Commonwealth Bureau of Meteorology data for Cobar). Thus, the branch piles, with infiltration capacities of about 118 mm per hour, are potentially able to absorb intense rainfall. This is in marked contrast with the runoff slopes in general, where the potential infiltration rate is lower than the intensity of most rainfall.

The mechanisms by which infiltration capacity increases are probably complex, but they probably involve organisms that process litter and create an open, friable soil fabric. Soil fauna such as termites produce biopores that are likely to be the principal mode of water infiltration into the soil profile (Greene 1992). Accumulation of saltating sand particles also improves infiltration, but improved soil structure is the dominant factor.

Soil nutrients in surface layers, particularly nitrogen, carbon and CEC and electrical conductivity, increased in the plots treated with branches on both the grazed and ungrazed paddocks over the three years (Table 1). In the grazed paddock, as a whole, grazing pressures

Table 3. Differences in the number of ants between branch treatment plots and those with no branches on the grazed paddock, Lake Mere, New South Wales.*

	Branches	*No Branches*
Ants (# $m^{-2} \pm$ SE)	12.7 ± 0.6^b	2.9 ± 0.4^a

*Means with different superscripts are significantly different ($p < 0.01$, $n = 40$).

on herbage resources and stock impacts on soil surfaces were high throughout the experiment. This resulted in low plant cover on the paddock in general, providing little resistance to runoff and continuous disturbance of the soil surface. Thus, soil surface particles were detached and available for erosion processes. The constructed branch piles were able to trap these resources and, hence, became much richer. By contrast, the corresponding plots in the ungrazed paddock accumulated fewer resources. Higher than average rainfall in 1988 and 1989 promoted good herbage growth in the ungrazed paddock; this herbage reduced raindrop impact on the soil and obstructed overland flow. Thus, runoff was weaker and much less material was available for transfer.

Increases in organic nitrogen and carbon on the plots without branches over the three years in the ungrazed paddock (Table lb) were due to natural recovery processes associated with low utilization and generally good conditions for growth and nutrient cycling. By contrast, plots with no branches in the grazed paddock had similar values for organic nitrogen and organic carbon in 1988 and 1991 (Table la).

The increase in CEC in the 0–1 cm horizon is partly due to the increase in the individual cations and partly to improved exchange capacity due to organic carbon accumulation over the three years. The role of organic carbon in augmenting CEC in this soil type was reported by Tongway and Smith (1989). Values for available nitrogen and phosphorous showed trends similar to those for organic nitrogen and carbon, but they were too variable to be statistically significant.

The temperature regime within the soil beneath the branch piles is more moderate than in plots without branches, being cooler in the day and warmer by night. The evaporative losses will therefore be lower, and the microhabitat within these patches will be more favorable for many biota. Ants were much more numerous on the branch-treated plots than on other plots. A. Andersen (personal communication) considered that the ants most common in these plots (*Iridomyrmex* sp.) were preying on mites and spiders that had taken up residence in the litter trapped within the branches. In 1993, Greenslade and Smith (1994) found that densities of Collembola and Acari in soil cores, and Formicidae, Hemiptera, and some Collembola caught in pitfall traps, were significantly higher on the branch-treated plots than on control plots. The increase in soil mesofauna accounts in part for the large differences in measured infiltration rates, which are due to biopores created *de novo* by colonizing soil mesofauna.

Increased CO_2 release under branch treatments in the grazed paddock indicates that the rates of biological processes, such as litter decomposition, root respiration, and microbial respiration, are higher there than on the surrounding bare areas. This increased activity indicates that a wide range of biological interactions had been initiated by the branch treatment, probably because there were sufficient materials for rapid decomposition. This implies that a critical threshold has been crossed, though more work is required to test this.

This method of landscape rehabilitation, whereby patches were created to sequester scarce resources flowing around the landscape, was successful in restoring a wide range of soil properties, embracing the physical, chemical, and biological dimensions of fertility. The impact of this improvement in soil quality on the production of greater growth of perennial plants is also significant (Ludwig & Tongway 1996). Thus, the model of semi-arid landscape function in this landscape type proposed by Tongway and Ludwig (1990), whereby runoff and run-on processes interact with patches to concentrate scarce water and nutrient resources, was confirmed by the results of this experiment.

The procedure of landscape rehabilitation described here was also successful while grazing pressure was maintained, which has obvious advantages for practical pastoral management, in that destocking is not essential for the success of the method, and may even speed up the process of fertile patch formation. Performance standards for recognizing stages in soil rehabilitation are now available for monitoring the progress of rehabilitation (Tongway 1994; Tongway & Hindley 1995).

The importance of naturally fertile soil patches within the semi-arid landscapes of Australia is mirrored by similar soil patchiness in other arid and semi-arid regions of the world (Forman & Godron 1981; Garner & Steinberger 1989; Cornet et al. 1992). The processes invoked in patch maintenance were similar to ours. Patches vary greatly in scale. Within the *Acacia aneura* grove-intergrove semi-arid woodland of eastern Australia, smaller-scale patches such as *Acacia aneura* log-mounds also contain significantly higher levels of organic carbon and nitrogen than surrounding areas (Tongway et al. 1989). Thus, the rehabilitation of landscapes by the creation of patchiness is in accord with the natural patterning and functioning of landscapes.

Patchiness is identified with processes that conserve limited resources (water and nutrients) within these landscapes (Ludwig & Tongway 1995). Degradation can be defined as the loss of these processes—that is, the landscape loses its ability to respond to rainfall events. The role of patches in capturing or filtering such resources has been incorporated into a landscape flow-filter simulation model, which has been used to predict the total area of patch needed to conserve resources within semi-arid landscapes (Ludwig et al. 1994). This model has the practical application of specifying the relative areas that might be devoted to patch reconstruction when a landscape is rehabilitated.

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