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Changes of surface soil nutrients and sustainability of pastoralism on grazed hilly and steep land, South Island, New Zealand

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Abstract

Soil nutrients in topsoils (0–7.5 cm) on grazed hilly and steep land on 2 high country sheep farms with contrasting climate in the upper Waitaki district, South Island, New Zealand, were compared before and after a 14–15 year period. In addition, effects on soils of 2 farm management systems were compared by sampling similar soils on adjacent farms.

On a farm with mean annual rainfall of 700–1,000 mm (study area A) that had been fertilised and oversown, and grazed with about 1.6 ewe equivalents per hectare for 14 years, levels of exchangeable cations (Ca, K, Mg) increased in topsoils on sunny slopes, but there was little change on shady slopes. The Ca increase on sunny slopes was the increase to be expected from the amount of Ca contained in the superphosphate applied but increases of exchangeable K and Mg could not be explained by fertiliser additions. There was an overall 29% increase of CEC, 7.5% decline of base saturation, and decline of soil pH by 0.4 units over the 14 year period.

On a farm with mean annual rainfall of 500-600 mm (study area B) that had been grazed for 15 years with about 0.6 ewe equivalents per hectare but not fertilised or oversown, levels of exchangeable cations in topsoils declined. Base saturation values declined from 98% to 73% and pH declined by 0.4 units. Losses of Ca and Mg were greater than could be explained by direct effects of sheep grazing and we conclude that processes such as erosion or removal of vegetation and nutrients by rabbits are important loss pathways.

In the spatial comparison on land with mean annual rainfall of approximately 1,000 mm, oversown and fertilised soils (grazed with about 1.6 ewe equivalents per hectare) had higher levels of exchangeable cations, organic C and total N than soils that had neither been oversown or fertilised (grazed with about 0.6 ewe equivalents per hectare).

Questions of ecological and economic sustainability arise both on the moister and drier high country. On moister land like area A, if lime can be applied economically, and fertiliser can continue to be applied with positive financial returns, oversowing and fertilising may be sustainable on sunny slopes. The sustainability of pastoralism on shady slopes is more problematical. If on drier land losses of topsoil nutrients such as those measured on area B are widespread, they are considered to be unsustainable. Although the nutrients lost could be readily replenished using modest amounts of fertiliser and lime, the changes have occurred concurrently with declines of organic C and total N. Restoration of organic matter levels is likely to require either reduced grazing, or oversowing and application of fertiliser. Because oversowing and fertilising the drier high country is not financially viable except during periods of high commodity prices, both these options would require major changes in farm management and/or financial assistance with soil conservation measures.

Key Words: sustainable agriculture, New Zealand, high country, soil nutrients, grazing

Background

In the high country of the South Island of New Zealand, the 1970s and early 1980s were a time of agricultural development aided by government subsidies for oversowing, fertilising and fencing. The withdrawal of most subsidies in the 1980s, concurrently with the invasion of weeds like *Hieracium* sp. and briar (*Rosa rubiginosa* L.), and an explosion of rabbit numbers shortly after the removal of subsidised control in 1985, made the true costs of high country land development more evident and raised the question of both the ecological and economic sustainability of high country pastoralism (Hughes 1991). O'Connor and Harris (1991) estimated that European pastoralism, fire and grazing had resulted in a net loss of all major nutrients (N, P, K, S) from high country soils since 1850 and McIntosh et al. (1994a, 1994b) reported pH declines and soil organic matter changes on a farm scale in the South Island high country. This paper reports temporal and spatial soil nutrient changes on 3 high country sheep stations under different management.

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Characteristics of Study Areas and Previous Work

The areas chosen for study are in the upper Waitaki district of the South Island, New Zealand, between latitudes 44°S and 44°30'S (Fig. 1).

Temporal soil changes on grazed land which has been oversown and fertilised were examined in the Longslip study area (A) consisting of a spur of Dromedary Hill (1,664 m) southwest of the Ahuriri River, North Otago. The spur ranges from 685 to 1,190 m altitude and has a mean annual rainfall of 700–1,000 mm. Underlying rocks are Chlorite II subschist (Gair 1967). Soils have been previously mapped in the Kaikoura and Omarama sets (N.Z. Soil Bureau 1968). Soils were described by McIntosh et al. (1981) and in the New Zealand Soil Classification (Hewitt 1992) are provisionally defined as Brown Soils and Pallic Soils. The soils are typically formed in thin loess (c. 10 cm thick) over gravelly or very gravelly colluvium. The Pallic soils occur on lower-altitude sunny slopes. In USDA Soil Taxonomy (Soil Survey Staff 1994) the Brown Soils correspond approximately to Cryochrepts and Dystrochrepts and the Pallic soils to Ustochrepts. Between 1980 and 1992 area A was oversown with clovers and a total of 1,100 kg/ha of sulphur-superphosphate (28% total S) was applied.

Temporal soil changes on grazed land which has neither been oversown or fertilised were examined in the Glencairn study area (B) consisting of a spur on the eastern side of the Benmore Range. The spur ranges from 440 to 810 m altitude and has a mean annual rainfall of 500–600 mm. Underlying rocks are greywacke (Gair 1967). Soils were previously mapped in the Meyer and Omarama sets (N.Z. Soil Bureau 1968). As for area A, soils are typically formed in thin loess overlying gravelly or very gravelly colluvium. Soils were described by McIntosh et al. (1981) and have recently been remapped and classified as Pallic, and Recent Soils (Landcare Research, unpublished data). In USDA Soil Taxonomy (Soil Survey Staff 1994) the soils correspond approximately to Eutrochepts and Ustochrepts.

Soils under contrasting pastoral management were examined in study area C in a spatial comparison spanning the boundary of Longslip and Ben Avon Stations on slopes either side of the Avon Valley. Altitude ranges from 800 to 1,000 m, and mean annual rainfall is approximately 1,000 mm. Underlying rocks are Chlorite II subschist (Gair 1967) and soils are Brown Soils previously mapped in the Kaikoura set (N.Z. Soil Bureau 1968). As for area A, soils are typically formed in thin loess overlying gravelly or very gravelly colluvium. In USDA Soil Taxonomy (Soil Survey Staff 1994) the soils are Dystrochrepts. Sites in area C have had contrasting management: soils on Longslip have been oversown with clovers and a total of 1,100 kg/ha of sulphur-superphosphate (28% total S) has been applied between 1980 and 1992, whereas soils on Ben Avon have not been fertilised or oversown.

No lime has been applied to any area. Each area is grazed by merino sheep. Stocking rates in area A have averaged 1.6 ewe equivalents per hectare (ee/ha) between 1980 and 1992 (about 2.1 ee/ha and 1.1 ee/ha on sunny and shady faces respectively). Stocking rates in area B have averaged 0.6 ee/ha between 1980 and 1992. In area C stocking rates on Longslip have averaged

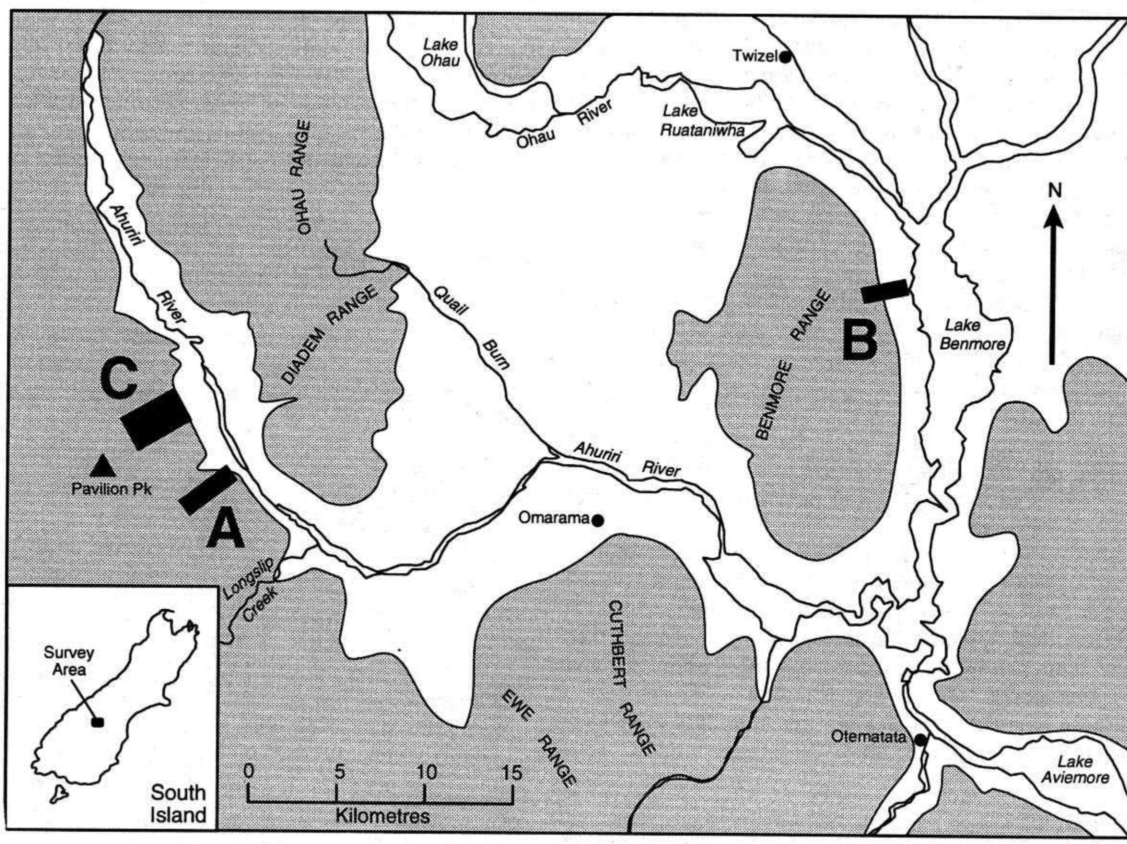

Fig. 1. Location map.

about 2.1 ee/ha, and on Ben Avon about 0.6 ee/ha. Wild rabbits are also present in each area.

In area A the present vegetation is dominated by introduced white clover (*Trifolium repens* L.) and grasses (e.g. sweet vernal (*Anthoxanthum odoratum* L.) and browntop (*Agrostis capillaris* L.)) with the native narrow-leaved snow tussock (*Chionochloa rigida* (Raoul) Zotov) common above 1,000 m altitude. In area B the vegetation is dominated by *Hieracium pilosella* L. and sweet vernal and the native hard tussock (*Festuca novae-zelandiae* Cockayne) and annuals with up to 40% bare ground. In area C the vegetation on Longslip Station is similar to that of area A, whereas the vegetation on Ben Avon Station consists of native herbs (e.g. *Leucopogon fraseri* Cunn. and scabweed (*Raoulia australis* Hook.f.)) and grasses (e.g. hard tussock and blue tussock (*Poa colensoi* Hook.f.)) and *Hieracium pilosella* and up to 50% bare ground.

McIntosh et al. (1994a, 1994b) described the soil pH, organic C and total N changes that have occurred since 1978 on areas A and B. Volume-weight data for surface soils of areas A and B was published by McIntosh et al. (1994b).

Methods

Site Selection

In 1992 topsoils in area A were grid sampled at 36 sites previously sampled in 1978. The samples were taken from an altitude sequence as shown in McIntosh et al. (1981). There were 18 paired sites on midslope and upper midslope positions on the shady aspect, and a similar configuration of paired sites on the sunny aspect. At each site the same sampling procedure was followed in 1978 and 1992: 15 soil cores 2.54 cm diameter and 7.5 cm deep were taken from an area approximately 10 $m^2 \times 10$ m^2 and bulked. Field duplicates of bulked samples were taken in 1978 but, as there was little difference between results of duplicates, single bulked samples were taken in 1992.

In 1993 area B was grid sampled at 24 sites previously sampled in 1978 (McIntosh et al. 1981). The sampling pattern and procedure was similar to that described for area A.

Area C was sampled for the first time in 1994. Ten sites were chosen on Longslip, representing the maximum possible range of altitudes (800–1,000 m) and aspects, and these were matched with 10 sites on Ben Avon having the same altitudes and aspects. The topsoil sampling procedure was similar to that described for area A. Soilforms (Hewitt 1992, Clayden and Webb 1994) were also closely matched and those that had different parent material, or soil depth outside specified limits, were rejected. Stock camps were avoided.

Samples for the comparisons were limited to 0–7.5 cm depth because: (a) 1978 sampling was to 7.5 cm depth. (The 1978 investigation was to establish landscape-related soil chemical patterns rather than to establish baseline monitoring sites.); (b) the gravelly nature of the subsoils made routine coring of subsoils, for the purpose of collecting a bulk sample at each of the 80 sites, impossible.

Soil Chemistry

In areas A and B analysis for exchangeable cations and cation exchange capacity (CEC) was by the ammonium acetate pH 7.0 leaching method (Blakemore et al. 1987), both in 1978 and 1992/3. Detailed methodology changed slightly between sampling dates: for 1978 samples leaching was by gravity extraction and CEC was determined by ammonia distillation. For 1992/3 samples leaching was by controlled rate suction and CEC was determined by ammonia analysis using an autoanalyser. Results by both methods are identical except that low cation and CEC values may be obtained if gravity extraction is rapid and allows by-passing of a proportion of the soil volume by the leaching solution to occur (B. Daly, Landcare Research laboratory, personal communication). Analysis for acid-soluble P (Pa), acid-soluble P after ignition (Pi) and organic P (Po) (Po = Pi–Pa) was by the 0.5M H_2SO_4 method (Blakemore et al. 1987) both for the 1978 and 1992/93 samples. Selected samples in study area B (in which soils of highest pH occur) were tested for electrical conductivity using a 1:1 soil: water ratio.

In area C organic C and total N were determined by standard methods used at Invermay Agricultural Centre, AgResearch, Mosgiel and exchangeable cations were determined by unbuffered silver thiourea extraction (Blakemore et al. 1987).

Statistical analysis was by paired t-tests. The results from the 1978 sampling of the 36 sites in area A and 24 sites in area B were paired with the 1992/93 results. In area C the 10 Longslip sites were paired with the 10 Ben Avon sites.

Results and Discussion

(1) Temporal Soil Changes in a Farm System with Fertiliser Inputs (Area A, Longslip)

Exchangeable Ca, K, Mg and CEC have increased significantly ($P \leq 0.05$) on sunny slopes only (Table 1). Changes in these nutrients follow the pattern for total N, which increased only on sunny slopes (McIntosh et al. 1994b). The only significant change of P status is the increase of overall Pa values by 4 mg/100g.

The sulphur-superphosphate applied to Longslip between 1978 and 1992, if applied evenly over the soils of study area A, and retained in soils at 0–7.5 cm depth, would have increased soil Ca by 220 kg/ha. The observed increase of exchangeable Ca on sunny slopes is equivalent to an increase of 223 kg Ca/ha. The much smaller (non-significant) increase on shady aspects indicates that Ca removal from 0–7.5 cm soils on shady slopes has taken place. Possible removal pathways are to stock camps, to animal products, to sunny aspects, or to soil layers below 7.5 cm depth by leaching, or a combination of these pathways. (The observations made in this study are not sufficient for a model of nutrient dynamics to be constructed.) The increase of exchangeable K on sunny slopes approximates to 46 kg/ha and the Mg increase to 19 kg/ha. These increases cannot be attributed to fertiliser additions and are likely to be caused either by uptake and cycling of nutrients from soil depths not sampled, or transfer of nutrients to these sites by stock. That animals are involved in the cycling process is indicated by the small or negative effects on shady slopes not favoured by stock: pastures are eaten on these slopes but urine and dung are probably deposited in disproportionably greater amounts on sunny slopes where stock spend most time. If such transfer is occurring, it could be stopped by erecting more fences. The increase of CEC on sunny slopes is explained by the increase of soil organic carbon (from 3.2% to 6.4%) that has occurred on sunny slopes as the result of fertilising and oversowing (McIntosh et al. 1994a). The increase of CEC has caused

Table 1. Changes of pH, CEC and soil nutrients from 1978 to 1992 in study area A (Longslip).

Nutrient		Date	Shady (n=18)			Sunny (n=18)			Overall (n=36)		
			Value	Diff.	Signif.	Value	Diff.	Signif.	Value	Diff.	Signif.
pH		1978	5.74			5.87			5.81		
		1992	5.34	–0.40	***	5.46	–0.41	***	5.40	–0.41	***
Exch. Ca	(cmol(+)/kg)	1978	3.23			4.91			4.07		
		1992	3.42	+0.19	NS	7.10	+2.19	***	5.26	+1.19	***
Exch. K	(cmol(+)/kg)	1978	0.82			1.10			0.96		
		1992	0.77	–0.05	NS	1.33	+0.23	**	1.00	+0.04	NS
Exch. Mg	(cmol(+)/kg)	1978	0.66			1.02			0.84		
		1992	0.66	0	–	1.34	+0.32	*	1.00	+0.16	*
Exch. Na	(cmol(+)/kg)	1978	0.00			0.00			0.00		
		1992	0.02	+0.02	NA	0.01	+0.01	NA	0.02	+0.02	NA
Σ cations	(cmol(+)/kg)	1978	4.75			7.07			5.91		
		1992	4.86	+0.11	NS	9.78	+2.71	***	7.31	+1.40	**
CEC	(cmol(+)/kg)	1978	15.4			12.6			14.0		
		1992	16.8	+1.4	NS	19.1	+6.5	***	18.0	+4.0	***
BS	(%)	1978	31			55			43		
		1992	29	–2	NS	50	–5	*	40	–3	*
Pi	(mg/100 g)	1978	90			90			90		
		1992	89	–1	NS	97	+7	NS	93	+3	NS
Pa	(mg/100 g)	1978	23			29			26		
		1992	27	+4	NS	33	+4	NS	30	+4	*
Po	(mg/100 g)	1978	67			61			64		
		1992	62	–5	NS	64	+3	NS	63	–1	NS

Because of rounding of the last significant figures in computations, tabulated values may not appear to match values derived from other tabulated means. Pa = P soluble in 0.5M H_2SO_4, air-dry soil; Pi = P soluble in 0.5M H2SO4, ignited soil; Po = Pi–Pa
BS = Base saturation = (Σ cations/CEC) × 100
NA: exchangeable Na values were at limit of detection using 1978 instrumentation, therefore no statistical comparison is possible.
* = significant difference ($P \leq 0.05$); ** = significant difference ($P \leq 0.01$); *** = significant difference ($P \leq 0.001$). NS = not significant ($P > 0.05$).

base saturation (BS) to decline on sunny slopes from 55% to 50% over the 1978–1992 period, despite the increase of total exchangeable cations.

The 1,100 kg of sulphur-superphosphate applied to Longslip between 1978 and 1992, if applied evenly over the soils of study area A, and retained in soil at 0–7.5 cm depth, would have resulted in an increase in soil Pi of 100 kg/ha. In fact the average Pi increase (Table 1) is not significant and is only 3 mg/100 g, equivalent to a P increase of 17 kg/ha. Thus fertiliser P has either been leached to greater depth, or has been removed from sampling sites in the form of sheep products or by dung transfer to stock camps. P leaching is unlikely in these soils, which have P retention in the 26–45% range (McIntosh et al. 1981). From the non-significant Pi increase of 7 mg/100g on sunny slopes and decrease of 1 mg/100 g on shady slopes we infer that the dung transfer pathway may be important. The small significant ($P \leq 0.05$) overall increase of Pa and the small non-significant decline of overall Po indicates that the additional P applied as fertiliser has not accumulated as Po, despite the large increase of organic C over the 1978–1992 period (McIntosh et al. 1994a).

(2) Temporal Soil Changes in a Farm System without Fertiliser Inputs (Area B, Glencairn)

Between 1978 and 1993 exchangeable Ca, K and Mg values declined on both sunny and shady slopes (Table 2), but the decline of exchangeable K on sunny slopes was not significant ($P > 0.05$). Soils tested for electrical conductivity gave results in the range 43–59 uS/cm indicating that no free salts were present.

Exchangeable Ca values declined most (27%) followed by Mg (14%) and K (5%). CEC increased significantly ($P \leq 0.001$) on sunny slopes. As a result of the decline of total exchangeable cations, and the increase of CEC, overall base saturation (BS) declined from 98% to 73%, the decline being greater on shady slopes. Po declined and Pa increased on both sunny and shady slopes. Overall the decline of Po was matched by the increase of Pa.

The overall losses are equivalent to 380 kg/ha Ca, 21 kg/ha Mg and 14 kg/ha K, which equate to annual losses of 25 kg/ha Ca, 1.4 kg/ha Mg and 0.9 kg/ha K. Analysis of deeper soils (7.5–25 cm) at 2 sites on Glencairn showed that pH, organic C, total N, P fractions and exchangeable cations had similar values in both grazed and ungrazed (fenced) areas, and that only exchangeable K values were significantly lower after 15 years of grazing (Landcare Research, unpublished data). The measured soil losses calculated above from topsoil (0–7.5 cm) data are therefore considered to be approximately the total losses for Ca and Mg, but K loss may have been underestimated. The herbage dry matter at the site contains 0.9% Ca, 0.3% Mg and 1.3% K (Landcare Research, unpublished data) and at a stocking rate of 0.6 ewe equivalent/ha (ee/ha), and assuming a daily dry matter intake of 1.1 kg per sheep, the nutrients eaten annually by stock would be approximately 2.2 kg/ha Ca, 0.7 kg/ha Mg and 3.1 kg/ha K. The actual Ca and Mg losses from topsoils were therefore respectively about 10 times and double the estimated intake of these nutrients by sheep, and therefore direct effects of sheep grazing such as transfer of nutrients to stock camps and loss of sheep products cannot explain the overall soil nutrient decline. A similar conclusion applies to N values: McIntosh et al. (1994b) noted that top-

Table 2. Changes of pH, CEC and soil nutrients from 1978 to 1992 in study area B (Glencairm).

Nutrient		Date	Shady (n=12)			Sunny (n=12)			Overall (n=24)		
			Value	Diff.	Signif.	Value	Diff.	Signif.	Value	Diff.	Signif.
pH		1978	6.24			6.36			6.30		
		1993	5.70	–0.54	***	6.04	–0.32	***	5.87	–0.43	***
Exch. Ca	(cmol(+)/kg)	1978	11.47			8.51			9.99		
		1993	7.68	–3.79	***	6.91	–1.60	***	7.30	–2.69	***
Exch. K	(cmol(+)/kg)	1978	0.87			0.95			0.91		
		1993	0.82	–0.05	**	0.90	–0.05	NS	0.86	–0.05	**
Exch. Mg	(cmol(+)/kg)	1978	1.86			1.57			1.71		
		1993	1.47	–0.39	**	1.47	–0.10	*	1.47	–0.24	***
Exch. Na	(cmol(+)/kg)	1978	0.02			0.01			0.02		
		1993	0.05	+0.03	NA	0.04	+0.03	NA	0.05	+0.03	NA
Σ cations	(cmol(+)/kg)	1978	14.39			11.03			12.71		
		1993	10.02	–4.37	***	9.33	–1.70	***	9.67	–3.04	***
CEC	(cmol(+)/kg)	1978	14.6			10.3			12.5		
		1993	15.0	+0.4	NS	11.7	+1.4	***	13.4	+0.9	***
BS	(%)	1978	96			100			98		
		1993	67	–29	***	80	–20	***	73	–25	***
Pi	(mg/100 g)	1978	106			73			89		
		1993	102	–4	NS	77	+4	NS	89	0	–
Pa	(mg/100 g)	1978	39			36			37		
		1993	42	+3	*	42	+6	*	42	+5	**
Po	(mg/100 g)	1978	67			37			52		
		1993	58	–9	**	35	–2	NS	47	–5	**

Because of rounding of the last significant figures in computations, tabulated values may not appear to match values derived from other tabulated means. Pa = P soluble in 0.5M H_2SO_4, air-dry soil; Pi = P soluble in 0.5M H2SO4, ignited soil; Po = Pi–Pa
BS = Base saturation = (Σ cations/CEC) $\times$ 100
NA: exchangeable Na values were at limit of detection using 1978 instrumentation, therefore no statistical comparison is possible.
* = significant difference ($P \leq 0.05$); ** = significant difference ($P \leq 0.01$); *** = significant difference ($P \leq 0.001$). NS = not significant ($P > 0.05$).

soil (0–7.5 cm) N declined by 400 kg/ha between 1978 and 1993 but the N eaten by stock over this time period (calculated from the stocking rate and N content of herbage) is estimated to be 60 kg/ha. Therefore about 340 kg/ha of N has been lost from topsoils by means not directly related to sheep intake. The annualised K loss (0.9 kg/ha) is less than the estimated annual K intake by stock (3.1 kg/ha) and could, in theory, be accounted for by transfer of K to stock camps. However, in view of the figures for other cations and N, and the ability of these micaceous soils to supply K from non-exchangeable forms of "reserve K" in the soil (Kirkman et al. 1994), and exchangeable K decline in deeper soils (see above), we consider that measurements in 0–7.5 cm soils have probably underestimated K removal.

There have been no fires in the 1978–1993 period and increased vegetation uptake could not account for the cation and N losses as vegetation cover has decreased rather than increased over the period in question (R.B Allen, Landcare Research, unpublished data). Significant leaching losses are considered unlikely because of the low rainfall in the study area. We therefore conclude that the cation and N losses must be accounted for by other processes, e.g. losses associated with rabbit grazing and/or erosion.

Part of the 7% overall increase of CEC between 1978 and 1993 may be attributable to the improved extraction for NH_4^+ in the 1993 samples. Even if the increase of CEC is discounted, the decline of cations and base saturation (BS) values over the 15-year period is nevertheless large and has occurred together with increased acidity, and a decrease of organic C and total N in these soils (McIntosh et al. 1994b), demonstrating how rapidly fertility and organic matter status of drier high country soils can change under pastoral use.

(3) Spatial Comparison of Soils Under Contrasting Pastoral Management (Area C, Longslip and Ben Avon)

Uniformity of Paired Sites

Establishing pedological uniformity of the paired profiles in area C was a prerequisite for attributing topsoil chemical differences to management influences. All soils were Brown Soils in the New Zealand soil classification (Hewitt 1992). After eliminating sites with very different soils during site selection, the main factors which varied in the 10 selected pairs were pH, degree of stoniness and depth.

Seven pairs of profiles were matched exactly to the level of the fourth category of the New Zealand soil classification, the soilform (Clayden and Webb 1994). These soils were classified as Typic Acid Brown Soils, angular-stony, rapid (5 profiles), Typic Acid Brown Soils, moderately deep, moderate (1 profile), and Acidic Orthic Brown Soils, lithic, rapid (1 profile). The remaining 3 pairs had different soil classification: a pair of Typic Acid Brown Soils had Mm and Md depth classes (soil depth of 55 cm versus 90+ cm) and 2 pairs belonged to contrasting groups (Acidic Orthic versus Typic Acid) because of the different pH values of their respective Bw horizons. However, among the 10 paired profiles, pH values of the Bw horizons did not differ significantly (P>0.05).

Because of the exact correspondence of soil classification for seven of the 10 pairs, and the relatively minor differences of subsoil pH, stoniness and depth in the remaining 3 pairs, we are confident that there was no systematic difference of soil morphology or chemistry between the Longslip and Ben Avon sites prior to the 2 farms being differently managed after 1978.

Soil Differences

There was no significant difference ($P > 0.05$) of topsoil pH between pairs (Table 3). Exchangeable Ca, K, and Mg values were respectively 97%, 61%, and 55% higher on Longslip than on Ben Avon, all differences being significant ($P \leq 0.01$). Organic C and total N were 40% and 52% higher respectively on Longslip than on Ben Avon, and both differences were significant ($P \leq 0.01$). The differences of exchangeable Ca, Mg and K between Longslip and Ben Avon Stations are equivalent to 166 kg/ha Ca, 22 kg/ha Mg and 60 kg/ha K.

Table 3. Comparison of topsoil (0–7.5 cm) chemical properties at 10 paired sites on Longslip and Ben Avon Stations, study area C.

Property	Longslip	Ben Avon	Significant Difference
pH	5.3	5.3	–
C (%)	5.2	3.7	**
N (%)	0.35	0.23	**
Exch. Ca (cmol(+)/kg)	3.32	1.69	***
Exch. Mg (cmol(+)/kg)	0.79	0.49	**
Exch. Na (cmol(+)/kg)	0.04	0.03	NS
Exch. K (cmol(+)/kg)	0.79	0.49	***

* = significant differences ($P \leq 0.05$); ** = significant difference ($P \leq 0.01$); *** significant difference ($P \leq 0.01$). NS = not significant ($P > 0.05$).

From Table 3 alone it is not possible to determine whether exchangeable cations on Longslip have increased, or whether those on Ben Avon have declined, or both. The lack of baseline data demonstrates the difficulty of interpreting spatial studies like the area C comparison in isolation. However, the evidence from the area A temporal study, previously discussed, shows that exchangeable cations have increased on Longslip, both as a result of direct fertiliser inputs (Ca) and possibly by enhanced nutrient cycling or transfer (Ca, Mg and K). Organic C on Longslip increased after oversowing and fertilising (McIntosh et al. 1994a), while grazing alone on Glencairn was associated with organic C and total N decline (McIntosh et al. 1994b). Therefore the differences observed in area C could be explained both by organic C increase on Longslip and organic C and total N decline on Ben Avon over the last 16 years. Further temporal monitoring in area C is required to confirm deduced temporal trends.

Conclusions

Moister Hilly and Steep Country (Areas A and C)

The increase of exchangeable cations and organic C on fertilised and oversown moister hilly and steep country indicates that the oversowing and fertilising has positive soil effects, and insofar as ecological sustainability can be judged by soil factors that can be measured by surface sampling, the evidence generally indicates that oversowing and fertilising is sustainable in the short term. However, we note that the positive effects are largely confined to sunny slopes, and the pH decline previously noted will at some time require correction. If fertilising continues to be economic, and liming of similar high country is less expensive than estimated by McIntosh et al. (1994a), continued intensified pastoral use of moister hilly and steep high country (like that of area A) could be sustainable. However, in today's economic climate, the financial returns from developing moister hilly and steep country similar to area A have been questioned (G.I. Ogle and R.G. Patterson, unpublished report). Consequently, although the soil changes (other than pH decline) brought about by fertilising and oversowing are positive, the sustainability of fertilising and oversowing may eventually be determined by financial factors, which raises the important question of what soil changes might be expected if fertilising were to cease.

We consider that in moister high country like area A the most sustainable system may be one that minimises risk (arising from climate and commodity price variation) and maintains biodiversity while at the same time replacing nutrients lost by grazing. Such a system will involve oversowing and fertilising so that stocking rates can be significantly raised, without total replacement of the low-yielding but resilient and well-adapted native flora. Achieving this balance between introduction of desired pasture species, maintenance of biodiversity, increase of soil fertility and soil organic matter and profitability will require careful soil and vegetation monitoring.

Drier Hilly and Steep Country (Area B)

The results in this paper are the first report of measured large changes of topsoil nutrients occuring on a farm scale on unfertilised dry South Island high country under pastoral use. The large changes of topsoil nutrients and organic C that have occurred since 1978 demonstrate how sensitive the drier soils are to pastoral land use, although calculations show that many of the changes are likely to be indirect effects of grazing rather than directly caused by nutrient uptake and transfer. While it is clear that continued losses of this magnitude would be unsustainable, the measured soil Ca, Mg and K losses could be readily replaced by fertilising. For example, the total Ca, Mg, and K lost over 15 years could be replenished by applying 1.1 t/ha of agricultural lime, 105 kg/ha of magnesium sulphate and 28 kg/ha of potassium chloride. Fertilising the drier hilly and steep country however may bring other problems, e.g. a proliferation of briar *(Rosa rubiginosa).*

Reversing the organic C and total N decline noted by McIntosh et al. (1994b) is not so straightforward and may require either reduced grazing to enable more organic matter to return to soils as litter, or higher plant productivity through oversowing and fertilising to enhance litter, dung and urine returns. Both these options would have big impacts on total farm management: reducing grazing on the hilly and steep land would require development of grazing elsewhere on the farm to maintain farm viability. The alternative of legume introduction would probably require soil conservation subsidies as financial analysis by B. Aubrey has shown that on Glencairn Station the moderate average dry matter yields of about 4 t/ha/yr from fertilised pastures (McIntosh et al. 1985, Boswell and Swanney 1990), combined with climate-related seasonal yield variation, mean that oversowing and fertilising is risky and uneconomic except during periods of highest wool prices (Ross et al. 1993). It is therefore likely that the objective of maintaining soil organic matter and nutrient levels while grazing continues on the drier high country will be achievable only with financial assistance from outside agencies.

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