Nutrient and contaminant profiles of soil, herbage and dung from sheep grazed pastures with varying phosphorus fertiliser histories

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Abstract

Long-term phosphorus (P) fertiliser application in hill country pastures improves productivity and increases the risk of contaminants, particularly cadmium (Cd), that accumulate in soil. This study explores the macronutrient and Cd profiles of soil, herbage, and sheep dung as influenced by contrasting P fertiliser histories: no fertiliser (NF), low fertiliser (LF), and high fertiliser (HF) input. Soil samples from HF showed higher Olsen P, total P, sulphate-S and total Cd compared with NF and LF. Herbage from HF contained higher concentrations of P, K, S, and Cd, with a shift in botanical composition favouring perennial ryegrass. Compared with NF, dung samples from HF had higher concentrations of N (2.4 vs 2.2%), P (0.97 vs 0.54%), and Cd (0.66 vs 0.21 mg/kg), and lower fibre content, indicating greater cycling of nutrients and contaminants through the animal. These findings highlight the legacy effects of P fertiliser use on nutrient and contaminant cycling in hill country systems and support efforts to model their long-term agroecological impact.

Keywords: grazing sheep, heavy metals, hill country pastures, livestock carrying capacity, soil contaminants,

Introduction

Phosphate fertiliser inputs have a positive effect on soil fertility and pasture productivity of hill country agroecosystems (Lambert et al. 2014; Mackay et al. 2021). Phosphate inputs are essential for the economic production of legume-based pastures, the main feed source for livestock agriculture in New Zealand. Unfortunately, non-essential heavy metals such as cadmium (Cd) are present as contaminants in the phosphate rock (Syers et al. 1986), from which phosphate fertilisers are made, and this pollutant, along with nutrients added to pastures, cycles through the soil-plant-grazing animal system (Loganathan et al. 1995; Loganathan et al. 2003). Despite the presence of several other potentially toxic elements in phosphate rock posing a risk of accumulation in soils (Loganathan et al. 2003), Cd is used herein as a proxy for all contaminants. The extent of phosphorus (P) and Cd accumulation in pasture soils is largely driven by P fertilizer history, whereas phytoavailability of Cd is largely driven by soil pH, clay mineralogy and soil organic matter content (Williams and David 1973; Lambert et al. 2000; Kelliher et al. 2017).

Long-term phosphate fertiliser and grazing trials provide unique field laboratories for gaining insights into macronutrients and contaminants cycling through grazing systems. As dung is deposited on soil, nutrients and contaminants become part of soil-plant-animal systems, with contaminants as a risk to the animal (Lee et al. 1994) and receiving environments (Zhao et al. 2015). While much has been reported on macronutrients and Cd in soils and plants, much less is known about these elements in dung and the role they play in the soil-plant-grazing animal continuum. The objective of this study was to examine the three major pools (i.e., soil, herbage, dung) of macronutrients [nitrogen (N), P, potassium (K), sulphur (S)], carbon and contaminants (Cd) in a hill country grazing system, using data collected from three sheep dung disappearance trials conducted in 2020 and 2021.

Materials and Methods

Experimental site and fertiliser history

Three experiments were conducted to explore the effects of biological (dung chemistry and soil biology) and topographical (slope and aspect) features on sheep dung disappearance. The experiments were conducted at the Ballantrae Hill Country Research Station in the autumn of 2020 [Experiments 1 and 2 in Vibart et al. (2021)] and 2021 (Experiment 3). Briefly, Experiment 1 examined the effect of farmlet (three levels of P fertiliser and associated sheep stocking regimes), slope class (low <12º and medium 12-24º) and aspect (East E, Southwest SW, Northwest NW), and Experiment 2 examined the effect of farmlet, both as a source and placement of dung, on dung disappearance over time (Vibart et al. 2021). Experiment 3 was conducted the

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following autumn (2021) and was similar to that of Experiment 2 but added the slope class effect (low and medium). Topographical features at the experimental site are considered typical of North Island hill country grazing landscapes, with soils classified as Brown and Pallic soils with yellow brown / yellow grey earth intergrades, largely with imperfectly drained silt-loam textures (Hewitt, 1998).

Soil, herbage and sheep dung samples were collected from three long term, self-contained farmlets that have received either no single superphosphate (SSP) fertiliser (NF; 9.7 ha), 125 kg SSP/ha (LF; 8.1 ha) or 375 kg SSP/ha (HF; 6.8 ha) on an annual basis since 1980. Corresponding amounts of SSP used on these farmlets prior to 1980 (1973-1979) were 156, 156 and 425 kg SSP/ha (Lambert et al. 1986). Superphosphate fertiliser used over the decades has been made from blends of phosphate rock with varying P and Cd concentrations based on the source of the phosphate rock (Loganathan et al. 1995; Loganathan et al. 2003; Abraham 2020).

The farmlets are continuously grazed by breeding ewes, with ewe stocking rates adjusted to herbage growth rates and to a similar post-grazing biomass target across farmlets; overall, mean annual stocking rates on these farmlets have increased from about 6.9 (NF) to 10.6 (LF) and 16.0 (HF) stock units over the 1980-2005 period (Mackay et al. 2016), but have been declining since (Mackay et al. 2021).

Soil, herbage and dung sampling and analysis

Twenty soil cores (25 mm diameter) were collected and bulked for chemical and physical analysis at each of the 12 sites within farmlets (n = 2 slope classes × 3 aspects × 2 reps) according to Mackay et al. (2021). Soil samples were bulked and analysed for pH in water, total nitrogen (N), total carbon (C), Olsen P and total P, sulphate-S and extractable organic S (immediately available vs longer term supply), exchangeable cations [calcium (Ca), magnesium (Mg) and potassium (K) MAF Quick Tests (MAF QT), measures of plant available Ca, Mg and K], and total recoverable Cd (hereafter referred to as total Cd) via a commercial laboratory (Eurofins Food Analytics; www.eurofins.co.nz). Cores were extracted in depth increments, up to a 300-mm depth, but the results reported herein are limited to the top two layers (0-75 and 75-150 mm). Stainless steel rings (100 mm diameter, 75 mm deep) were used to determine bulk density (BD) at each soil depth.

Herbage samples from exclusion cages (placed on medium slopes; results not reported) and from neighbouring grazed pastures were collected from each farmlet for both chemical analysis and botanical composition, according to Lambert et al. (2014). Samples from both locations (six from exclusion cages and six from neighbouring grazed pastures within each farmlet) were analysed for concentrations of dry matter (DM), organic matter (OM), OM digestibility (OMd), crude protein (CP), soluble CP, neutral detergent fibre (NDF), NDF digestibility, acid detergent fibre (ADF), acid detergent lignin (ADL), soluble sugars, lipids, and macronutrients and Cd using near infrared spectroscopy (NIRS). A separate set of herbage samples was used for separation of plant green tissue (from dead tissue), into perennial ryegrass, other grasses, white clover, other legumes and other species, according to Lambert et al. (1986).

Samples of fresh, intact sheep dung were collected from each of the farmlets on several occasions (five sampling events in 2020 and twice in 2021). After each collection, samples within each farmlet were mixed thoroughly and analysed, according to Vibart et al. (2021). Briefly, subsamples were used to obtain DM concentration and conduct NIRS analysis. Fresh weights were recorded and subsequently dried in a forced-air oven (at 60°C) and ground (<2 mm) prior to chemical analysis. Samples were analysed for concentrations of dry matter (DM), organic matter (OM), fibre components (NDF and ADF), total C, total N, and P, K, S and Cd using NIRS.

Statistical analysis

Soil and herbage data were analysed according to a type III analysis of variance (ANOVA) with a treatment (farmlet) and blocking (experiment) structure using Genstat 23rd Edition (v. 23.1.0.651) supplied by VSN International Ltd. (www.vsni.co.uk). A similar structure was used for dung data, but with an unbalanced (for unequal number of samples between farmlets) ANOVA. Significance was established at $P<0.05$.

Results

Nutrient and contaminant profiles of soils

Soils in the farmlets are slightly acidic (pH≤5.4) and have high organic C concentrations (>5%) (Table 1). Topsoil (0-75 mm) P (Olsen P and total P), sulphate-S, Ca (Ca MAF quick test QT), and total Cd concentrations were higher ($P<0.001$) in samples collected from the HF farmlet, whereas Mg (MAF QT) was lower ($P=0.02$) in samples collected from this farmlet. Similar results were seen in the deeper layer (75-150 mm), with higher ($P<0.001$) P, sulphate-S, Ca, and total Cd, and lower ($P=0.004$) Mg (Mg MAF QT) in HF soil (Table 1). Within the HF farmlet, pools of total P (Figure 1) and total Cd (Figure 2), calculated from bulk density, concentration and soil layer depth, were greater in low slope (<12º) and E aspect locations.

Nutrient and contaminant profiles of herbage

Herbage samples from grazed pastures neighbouring the exclusion cages were of high DM concentration and relatively low nutritive value (i.e., mean values of OM

Table 1 Chemical and physical characteristics of soil samples collected from three farmlets that have received either no single superphosphate (SSP) fertiliser (NF), 125 kg SSP/ha (LF) or 375 kg SSP/ha (HF) on an annual basis since 1980 (n = 12 samples per farmlet). Numbers with different superscripts differ (P<0.05).

Item	Farmlet *NF*	*LF*	*HF*	*s.e.m.*	P ≤
Soil depth: 0-75 mm					
pH	5.4	5.3	5.3	0.04	0.41
Bulk density, Mg/m^3	0.85	0.87	0.84	0.038	0.85
Total C, %	5.6	5.3	5.8	0.39	0.68
Total N, %	0.43	0.41	0.47	0.032	0.48
Olsen P, mg/L	3^a	12^a	64^b	6.3	<0.001
Total P, mg/kg	376^a	456^a	1111^b	80.8	<0.001
Sulphate S, mg/kg	4.6^a	6.6^a	14.5^b	1.13	<0.001
Extractable Organic S, mg/kg	10.0	10.6	12.5	0.92	0.15
Ca MAF QT	3.2^a	4.2^b	5.8^c	0.30	<0.001
Mg MAF QT	22.8^a	21.8^a	16.0^b	1.74	<0.019
K MAF QT	8.8	9.6	8.7	1.27	0.88
Cd, mg/kg	0.08^a	0.13^b	0.31^c	0.020	<0.001
Soil depth: 75-150 mm					
pH	5.5	5.4	5.3	0.05	0.10
Bulk density, Mg/m^3	1.03	1.05	0.99	0.035	0.41
Total C, %	4.4	4.0	4.3	0.31	0.68
Total N, %	0.36	0.33	0.35	0.025	0.67
Olsen P, mg/L	3^a	8^a	39^b	4.8	<0.001
Total P, mg/kg	354^a	387^a	722^b	50.7	<0.001
Sulphate S, mg/kg	3.9^a	6.2^b	12.2^c	1.20	<0.001
Extractable Organic S, mg/kg	10.2	10.1	10.8	0.99	0.85
Ca MAF QT	2.7^a	3.4^b	4.5^c	0.27	<0.001
Mg MAF QT	18.8^a	17.7^a	12.2^b	1.35	0.003
K MAF QT	7.7	7.9	6.4	1.04	0.54
Cd, mg/kg	0.08^a	0.11^b	0.20^c	0.010	<0.001

Table 2 Chemical and botanical composition of herbage samples collected from three farmlets that have received either no single superphosphate (SSP) fertiliser (NF), 125 kg SSP/ha (LF) or 375 kg SSP/ha (HF) on an annual basis since 1980 (n = 6 samples per farmlet). Numbers with different superscripts differ (P<0.05).

Item	Farmlet *NF*	*LF*	*HF*	*s.e.m.*	*P* ≤
Chemical composition (DM basis)					
DM, %	36.9	35.5	32.7	3.56	0.71
OM, %	87.8	89.0	84.7	2.99	0.59
OM digestibility, %	50.7	53.6	48.7	2.15	0.29
CP, %	11.8	14.7	14.4	1.16	0.19
Soluble CP, % CP	35.3	40.8	38.0	3.57	0.57
NDF, %	56.4	56.9	55.2	2.76	0.91
NDF digestibility, %	35.0	37.2	41.0	4.22	0.60
ADF, %	27.7	27.6	29.3	1.38	0.63
ADL, %	4.1	4.1	4.2	0.20	0.77
Soluble sugars, %	5.7	4.9	4.6	0.59	0.42
Lipids, %	2.5	2.7	2.1	0.19	0.13
ME, MJ/kg DM	8.1	8.6	7.8	0.34	0.28
P, %	0.16^a	0.22^b	0.35^c	0.022	<0.001
K, %	0.97^a	1.16^a	1.45^b	0.116	0.031
S, %	0.19^a	0.22^a	0.28^b	0.014	0.001
Ca, %	0.50	0.52	0.65	0.045	0.07
Cd, mg/kg	0.12^a	0.22^b	0.55^c	0.058	<0.001
Botanical composition (DM basis)					
Green (G) tissue, %	39.4	45.5	51.1	5.79	0.39
Ryegrass, % G	4.7^a	11.7^a	32.8^b	5.06	0.004
Other grasses, % G	82.6^a	78.5^a	54.0^b	6.45	0.014
White clover, % G	4.4	3.9	8.0	2.32	0.41
Other legumes, % G	0.0	0.6	1.5	0.77	0.42
Other species, % G	8.3	5.3	3.7	3.12	0.58

digestibility and ME were 51%, and 8.2 MJ/kg DM, respectively) (Table 2). Phosphorus, K, S and total Cd concentrations were highest (P<0.01) in herbage samples from grazed pastures collected from the HF farmlet. Herbage in the NF and LF farmlets had P and S concentrations in herbage <0.23%. The presence of ryegrass and other grasses as components of green tissue was highest (P=0.01) in herbage samples collected from the HF farmlet.

Nutrient and contaminant profiles of dung

Measures of dung fibre concentration such as NDF (P=0.007) and ADF (P=0.005) were lower in dung samples collected from the HF farmlet, compared with dung collected from the NF and LF farmlet (Table 3). Conversely, concentrations of N (P=0.017), P (P<0.001), and Cd (P<0.001) were higher in dung collected from the HF farmlet. Cadmium concentrations were 0.21, 0.31 and 0.66 mg/kg in dung collected from the NF, LF and HF farmlets, respectively. The concentration of P in the dung was on average three times higher than the P concentrations reported in herbage across all farmlets. In comparison, the concentrations of Cd in dung collected from the NF, LF and HF farmlets were only 1.7, 1.4 and 1.2 times higher than in corresponding

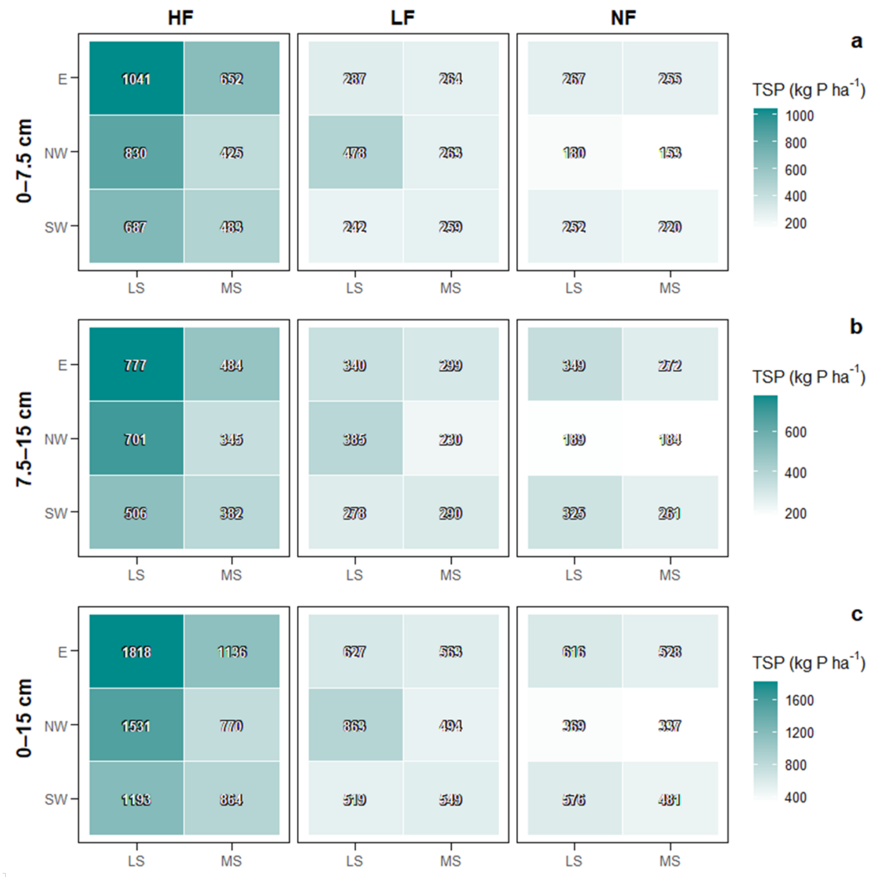

Figure 1 Total phosphorus (kg P ha^{-1}) at three soil depths: (a) 0-7.5 cm, (b) 7.5-15 cm and (c) 0-15 cm, across farmlets (NF = no SSP; LF = 125 kg SSP ha^{-1} yr^{-1}; HF = 375 kg SSP ha^{-1} yr^{-1} since 1980), slope classes (low slope LS = 0–12°; medium slope MS = 12–24°) and aspect locations (East = 35°–155°; Northwest = 275°–35°; Southwest = 155°–275°). Farmlet treatments have been maintained since 1980.

Table 3 Chemical composition of dung samples collected from three farmlets that have received either no single superphosphate (SSP) fertiliser (NF), 125 kg SSP/ha (LF) or 375 kg SSP/ha (HF) on an annual basis since 1980 [n = 8 (NF) and 17 samples (LF, HF) per farmlet]. Numbers with different superscripts differ (P<0.05).

Item (DM basis)	Farmlet						*P ≤*
	NF		*LF*		*HF*		
	Mean	*s.e.m.*	*Mean*	*s.e.m.*	*Mean*	*s.e.m.*	
OM, %	70.4	1.47	69.2	1.01	70.4	1.01	0.40
NDF, %	55.3^{a}	1.46	56.3^{a}	1.00	52.2^{b}	1.00	0.007
ADF, %	38.1^{a}	0.89	39.2^{a}	0.61	36.6^{b}	0.61	0.005
Total C, %	40.8	0.85	40.1	0.58	40.8	0.58	0.41
Total N, %	2.20^{a}	0.120	2.14^{a}	0.082	2.43^{b}	0.082	0.017
P, %	0.54^{a}	0.066	0.70^{b}	0.045	0.97^{c}	0.045	<0.001
K, %	1.34	0.180	1.30	0.114	1.42	0.114	0.47
S, %	0.32	0.011	0.31	0.007	0.33	0.007	0.09
Cd, mg/kg	0.21^{a}	0.028	0.31^{b}	0.028	0.66^{c}	0.028	<0.001

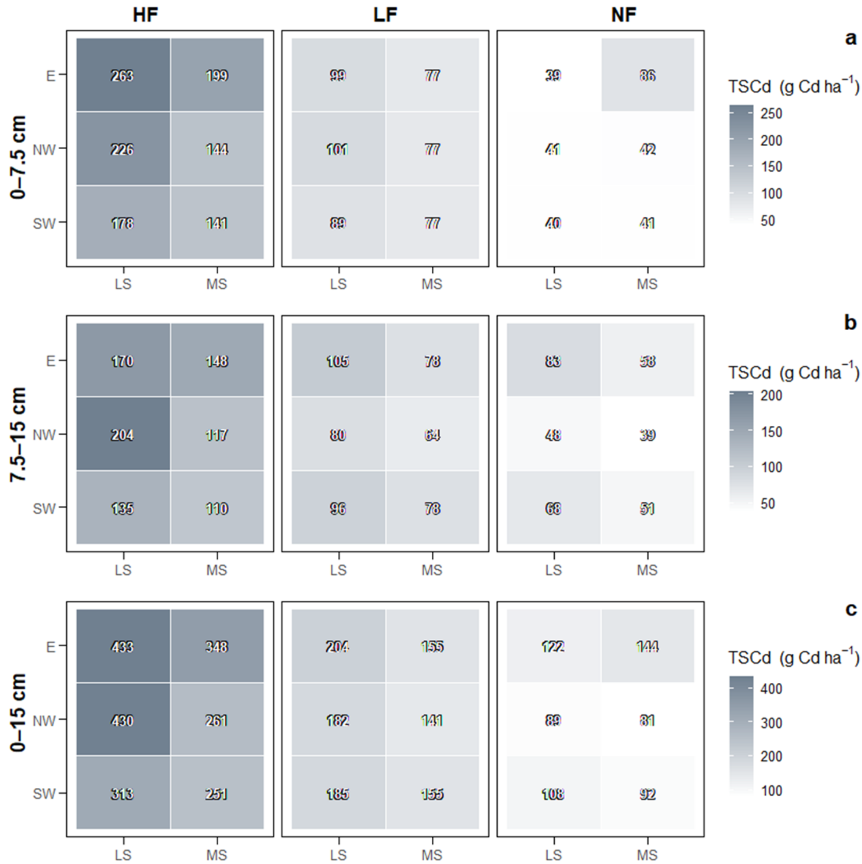

Figure 2 Total cadmium (g Cd ha^{-1}) at three soil depths: (a) 0–7.5 cm, (b) 7.5–15 cm and (c) 0–15 cm, across farmlets (NF = no SSP; LF = 125 kg SSP ha^{-1} yr^{-1}; HF = 375 kg SSP ha^{-1} yr^{-1} since 1980), slope classes (low slope LS = 0–12°; medium slope MS = 12–24°) and aspect locations (East = 35°–155°; Northwest = 275°–35°; Southwest = 155°–275°). Farmlet treatments have been maintained since 1980.

herbage. Organic carbon and K concentrations in dung were not affected by fertiliser history.

Discussion

Phosphate fertiliser and associated grazing management history significantly altered macronutrient (namely P, S, Ca, and Mg) and Cd concentrations across the soil-plant-grazing animal continuum. Long-term application of superphosphate, particularly on the HF farmlet (a 250-kg difference in SSP applied on an annual basis since 1980 between the LF and HF farmlet), has led to a significant increase in plant-available P (Olsen P) and total P, sulphate-S, and total Cd in the topsoil layer, consistent with previous research on fertiliser-derived nutrient and contaminant accumulation (Loganathan et al. 1995; Lambert et al. 2000; Bilotto et al. 2022). Single superphosphate manufactured from blends of phosphate rock applied on site has differed in P and Cd concentrations over the decades. During the 80s and early 90s, total P ranged from 11.9 to 16.4% P and total Cd ranged from 5 mg Cd (Jordanian phosphate rock) to 71 mg Cd (Nauru Island phosphate rock) (Loganathan et al. 1995). During this period, most of New Zealand's superphosphate was manufactured from Nauru Island phosphate rock, with Cd concentrations of about 600 mg Cd per kg P (Syers et al. 1986). Since then, Cd concentrations in P fertilisers have been gradually declining since the implementation of a planned phased reduction in 1995 (Abraham 2020).

Cadmium concentrations in soil were within those reported previously. A national survey of New Zealand pasture topsoils (0-75 mm; n = 312 samples) that had received P fertilisers reported total Cd concentrations that ranged from 0.04 to 1.53 mg/kg, with a mean value of 0.44 mg/kg (Roberts et al. 1994). Although most Cd applied in association with phosphate fertilisers to undisturbed soils remains in the top few centimetres, the enrichment was also seen in the second soil depth (75-150 mm) (Table 1 and Figure 2), indicating downward movement and increased environmental risk

(Loganathan and Hedley 1997). Not surprisingly, total Cd concentrations in topsoil are highly correlated with total topsoil P concentrations (Loganathan et al. 2003).

Macronutrients (i.e., P, K, S, Ca) and Cd concentrations in pasture herbage from the HF farmlet are likely a reflection of both the higher inputs of P and S, and associated changes in botanical composition, with an increased presence of perennial ryegrass (33% of herbage green tissue) and a reduced presence of low fertility grasses (54% vs up to 83% in NF). The increased proportion of perennial ryegrass is likely to increase nutrient uptake efficiency and a shift in pasture diversity with intensive fertiliser use. Pastures in both the NF and LF farmlets were deficient in P and S, with concentrations in herbage lower than 0.23%, concentrations that are likely to restrict animal growth, NF herbage in particular. The P and S concentrations of herbage samples collected from the NF farmlet (0.16 and 0.19%, respectively) were below the dietary P and S requirements of rapidly growing young lambs reported by Grace et al. (2010) of 2.2 and 2.0 g/kg DM, respectively.

Animal tissue concentrations are a reflection of intake, as dietary Cd accumulates in the edible offal of livestock (Grace et al. 2010). Although the elevated Cd concentration in herbage from HF pastures (0.55 mg/kg DM) may not be sufficiently high to pose a risk to animal health (albeit subject to length of exposure to high Cd), when herbage Cd concentrations increased from 0.12–0.30 to 0.50–0.80 mg/kg DM, Cd concentrations in kidney, liver and muscle of sheep increased 2-4 fold within six months (Lee et al. 1996). However, Cd is poorly absorbed in ruminants (<1% of intake), and most dietary Cd is excreted in faeces (Lee et al. 1994).

Dung composition further illustrated the cycling of nutrients and contaminants. Ruminants play an important role in nutrient cycling in grazed grasslands. Nutrients recycled back to the soil-pasture system via excreta, are a significant input to these production systems. Higher P and Cd concentrations in dung from the HF farmlet reflected elevated dietary intake by animals grazing on enriched pastures. Notably, dung fibre concentration (NDF and ADF) was reduced in HF animals, suggesting improved digestibility of a more nutrient-dense sward, consistent with greater ryegrass presence. However, elevated Cd concentrations in dung also confirm that contaminants are returned to the soil via excreta, perpetuating a cycle of accumulation with potential implications for both soil health and potentially food safety over time (Loganathan et al. 1995; Roberts and Longhurst 2002).

These results emphasize the dual role of P fertiliser inputs; while enhancing pasture productivity and livestock nutrition, they simultaneously contribute to the accumulation and redistribution of contaminants such as Cd. This dual effect needs careful consideration as part of long-term P fertiliser strategies, particularly in landscapes with limited ability to buffer contaminant loads.

Conclusions

These studies contribute to our understanding of pools and flows of macronutrients and Cd across the soil-plant-grazing animal continuum and enable further advance in the modelling of these agroecosystems. From a pragmatic perspective, our results support the need for periodic monitoring of both nutrients and contaminants in soils, herbage and faeces. Further, the data are valuable for refining mechanistic models of nutrient and contaminant cycling in complex topographies e.g., Grass-NEXT in Bilotto et al. (2022) and CadBal in Gray and Cavanagh (2023), enabling more sustainable management of hill country systems. Future work should explore mitigation strategies to reduce Cd inputs and consider alternative fertiliser formulations with lower contaminant profiles.

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