Changes in soil fertility, biology and organic carbon under contrasting phosphorus fertiliser and sheep grazing management

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Abstract

The phosphorus (P) fertiliser and sheep grazing experiment established at Ballantrae in 1975 has become an invaluable field laboratory. In-depth experimental studies have explored the long-term link between P fertiliser inputs and pasture and animal production, including the impact of withholding P fertiliser. In this paper we report on changes in soil nutrient fertility, organic matter, biology and physical status of soil across three farmlets that are receiving different rates of P fertiliser. Since 2020, soil pH has dropped by 0.5 units. Prior to 2020 pH values showed very little change, averaging 5.3 over the previous 45 years, despite very limited use of lime. There has been a trend of declining exchangeable magnesium and potassium levels, with differences seen across slopes, while exchangeable calcium has been sustained in the two farmlets receiving P fertiliser. The measured declines in total nitrogen in soil and earthworm abundance are consistent with the decline in pasture production and sheep stocking rates. If we are to fully understand the implications of variable inputs and management for permanent pasture systems within a changing climate, we must continue monitoring and measuring such long-term field experiments.

Keywords: climate change, field experiment, longitudinal study, P fertiliser, soil biology, soil fertility

Introduction

The long-term phosphorus (P) fertiliser and sheep grazing experiment located at AgResearch's Ballantrae Hill Country Research Station, was established in 1975 to explore the interaction between soil fertility and grazing practices (Lambert et al. 1983; Lambert et al. 1986). Since its inception, focus has shifted to include investigation on the effect of withholding fertiliser (Lambert et al. 1990), a topic that has resurfaced in recent years. In the 1990s experimental work focused on nutrient cycling, transfer and losses across slopes (Saggar et al. 1990; Sakadevan et al. 1993) and exploring the long-term sustainability of pastoral systems (Lambert et al. 1995; Lambert et al. 2000). The impact of pasture management on soil organic carbon emerged as a topic of interest over the last 20 years, with research on both its role in soil processes and as a currency to offset greenhouse gas emissions (Mackay et al. 2021a).

Since the experiment started in 1975 global average atmospheric carbon dioxide has increased by 92 ppm and surface temperature has increased by roughly 0.75 °C (IPPC 2023). Contrary to the prevailing view that these changes would have a positive impact on primary production (largely based on modelling), the pasture and animal production data from the long-term experiment suggests primary production has, in fact, been declining for nearly 20 years (Mackay et al. 2023). A finding also reached by Chapman et al. (2025), in an analysis of DairyBase data.

It has been over 14 years since changes in soil nutrient fertility of the long-term P fertiliser and sheep grazing experiment were reported on (Mackay and Lambert 2011). In this paper, we report on the changes in soil pH and exchangeable cations (Ca, Mg and K) since 1975 in the three farmlets that vary markedly in their P fertiliser and sheep grazing histories and report on the current nutrient fertility, organic matter, physical properties and biology of the soil from across the three slopes from each of the three farmlets.

Materials and Methods

Location

The long-term experiment is set within the Ballantrae Hill Country Research Station, which is located on the foothills of the Ruahine ranges in the Southern Hawke's Bay, New Zealand (408180S, 1758500E). Ballantrae is typical of much of the North Island's steep, pastoral hill country, which covers 3.5 million ha, 28% of the total area of farmland in New Zealand. It is located 125 to 350 m above sea level with an average air temperature of 12.8°C and annual rainfall of 1270 mm, often distributed evenly throughout the year.

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Brown and Pallic Soils i.e. yellow-brown earths and intergrades to yellow-grey earths, and related steepland soils are prevalent (Hewitt 1998). They are classified as Andic Distrochrepts, Typic Distrochrepts and Typic Eutrochrepts, with a silt loam texture using the US taxonomy (Soil Survey Staff 1999). They are formed from tertiary sandstone, siltstone, and mudstone, with some loess influence in places

Experiment design and history

Four self-contained experimental farmlets, two receiving low P fertiliser (LF) and two receiving high P fertiliser (HF) inputs were established in 1975 (Lambert et al. 1990). All farmlets are set stocked with sheep. Since 1980, one of the LF farmlets has continued to receive 125 kg superphosphate (SSP)/ha/yr (LFLF) and has been stocked with sheep at 10.6 su/ha. The other LF farmlet has had fertiliser withheld since then (LFNF), with stocking rates slowly declining to a current stocking rate of 6 su/ha. One of the HF farmlets has continued to receive 375 kg SSP/ha/yr (HFHF) since 1980 and was stocked at 16.0 su/ha up until the early 2000's, but since then stocking rates have slowly been reduced to 14 su/ha. Measurements on the other HF farmlet, that has had fertiliser withheld since 1980 (HFNF), ceased in 2022 due to the loss of permanent sites within the farmlet with the construction of the new SH3 Ahua a Te Ahua a Turanga: Manawatū Tararua Highway.

Within each farmlet permanent monitor sites cover three slope classes (low (0-12°), medium (13-25°) and steep (>25°) and three aspects (centred on the North-East, North-West and South) each with two replicates. Three farmlets are reported on here (LFNF, LFLF, HFHF).

Measurements and analysis

Occasional measurements of soil fertility and pasture production have been made on the farmlets, since continuous monitoring ceased in 1988. Soil pH and exchangeable cations are reported for soil samples taken to a depth of 75 mm from each of the 18 sites in 1975, 1993, 2003, 2014 and 2020 within each of the three farmlets.

In September 2024, soil samples were again taken to 0-75 mm from the 18 permanent sites located within each farmlet. Soils were analysed for pH in water, Olsen P, exchangeable cations, total carbon (organic carbon) and nitrogen (Organic N) using a commercial laboratory (Eurofins Food Analytics; www.eurofins.co.nz). Exchangeable calcium (Ca), magnesium (Mg) and potassium (K) are reported as MAF Quick Test values rather than cmol+/kg. Bulk density (BD) and macroporosity was assessed to 75 mm depth at the time of sampling at all sites using 100 mm diameter stainless steel corers. Earthworm abundance and biomass was also assessed at each site by taking three soil samples of about 0.04 m^2 each to a depth of 250 mm. Earthworms were extracted in the laboratory by hand sorting. Fresh biomass was calculated by emptying earthworm gut contents in water, drying on tissue paper and recording weight.

Statistics

Analysis of soil data are limited to the calculation of the means and standard deviations within each farmlet, as the farmlets are not replicated. The percentage difference between farmlets was described for macroporosity and earthworm abundance.

Results

Changes in pH and quick test Ca, Mg and K

Until the soil sampling in 2024, soil pH values had averaged 5.3 across the three farmlets varying from 5.3 to 5.5 from 1975 through to 2020 (Figure 1). In 2024, pH values were all less than 5.0.

Quick test Ca in the HFHF soils have risen higher than in the other two farmlets after less than 10 years, while in the LFNF farmlet Ca levels have slowly fallen below the LFLF farmlet over the last 20 years (Figure 1). In all three farmlets quick test K has slowly declined throughout the long-term study, with the test values on average three units lower than when the study commenced. Quick test Mg has also shown a decline over the course of the study with the values declining from 27 to 20 on the LFNF and LFLF farmlet, respectively, from 1975 to 2024. The decline in quick test Mg has been more pronounced in the soil samples collected from the HFHF farmlet dropping from 25 to 16 over the course of the study.

Soil nutrient fertility in 2024

Soil pH averaged 4.8 across the three slope classes of the three farmlets (Table 1). Olsen P in the HFHF farmlets averaged 37 µg/ml across the three slope classes, ranging from 53 µg/ml on the low slope to 29 µg/ml on the high slope (Table 1). Olsen P values were lower on the other two farmlets (6 and 15 µg/ml for the LFNF and LFLF, respectively) and showed a smaller difference between slope classes (Table 1).

Quick test Ca values in the 0-75 mm soil depth in the HFHF were nearly twice those of the LFNF farmlet, with values for the LFLF being intermediate and showing little difference between slope classes (Table 1). Quick test K values were highest on HFHF low slopes, being twice those of the high slopes in the HFHF farmlet (Table 1). In contrast there was no difference in K levels with slope in the LFNF farmlet. Quick test Mg averaged 20 and 21 MAF QT on the LFNF and the LFLF farmlet, respectively (Table 1). There was also little difference in Mg values between slope classes in these two farmlets. In contrast, Mg values in the soil in HFHF decreased with increasing slope (20 on low slopes to 13 on high slopes).

Table 1 Soil pH, Olsen P and quick test calcium, potassium and magnesium in 0-75 mm soil depth averaged across three aspects and two replicates for the low, medium and high slope classes for the LFNF, LFLF and HFHF farmlets in 2024.

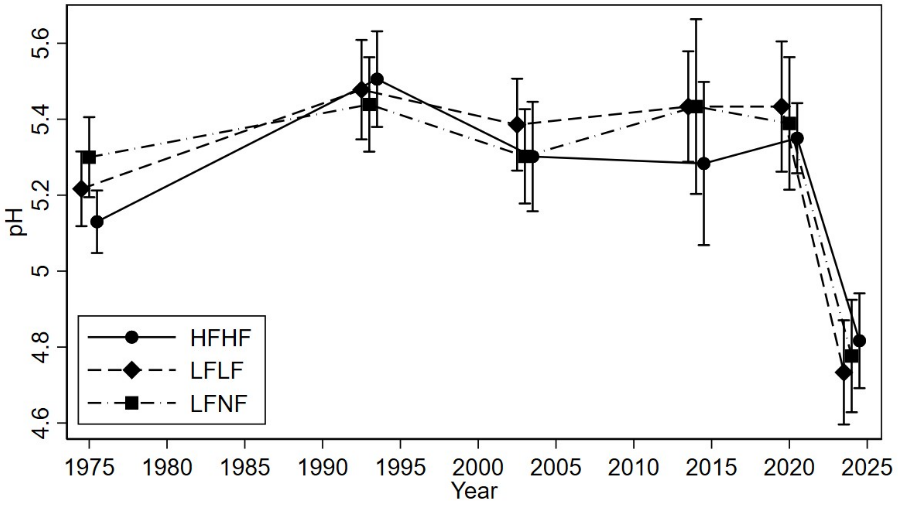
		pH		**Olsen P (ug/ml)**		**QT Ca (MAF QT)**		**QT K (MAF QT)**		**QT Mg (MAF QT)**	
Farmlet	Slope	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
LFNF	Low	4.8	0.2	6	1	3	1	8	3	19	6
	Medium	4.7	0.2	6	1	3	1	9	2	21	7
	High	4.7	0.1	5	1	3	1	7	2	20	3
LFLF	Low	4.8	0.2	17	10	5	1	8	5	21	6
	Medium	4.8	0.1	17	8	4	1	10	3	22	6
	High	4.7	0.2	11	5	4	1	5	2	19	3
HFHF	Low	4.8	0.1	53	9	7	1	13	7	20	7
	Medium	4.7	0.1	27	9	5	1	8	2	14	4
	High	4.7	0.2	29	10	5	1	5	1	13	1

Table 2 Total carbon and nitrogen, carbon to nitrogen ratio and macroporosity in 0-75 mm soil depth and earthworm abundance and biomass in 0-250 mm soil depth averaged across three aspects for the low, medium and high slope classes for the LFNF, LFLF and HFHF farmlets in 2024.

		Total C %		**Total N %**		**C:N Ratio**		**Bulk Density Mg/m^3**		**Macroporosity %**		**Earthworm Number/m^2**		**Earthworm Biomass g/m^2**	
Farmlet	Slope	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
LFNF	Low	7.7	2.3	0.61	0.19	12.4	0.6	0.7	0.12	18	3	302	279	86	64
	Medium	6.4	1.4	0.50	0.12	13.0	1.3	0.78	0.08	19	4	227	253	64	57
	High	5.2	0.9	0.39	0.06	13.3	0.8	0.9	0.13	24	6	132	132	49	14
	Mean	6.3	1.8	0.49	0.15	12.9	0.9	0.81	0.13	21	5	210	211	64	47
LFLF	Low	5.9	1.3	0.50	0.09	11.7	1.0	0.81	0.17	16	4	477	300	158	136
	Medium	5.9	0.8	0.48	0.07	12.6	0.9	0.86	0.05	18	3	315	187	106	49
	High	5.0	0.9	0.38	0.08	13.4	0.9	0.98	0.11	25	3	108	98	22	23
	Mean	5.6	1.1	0.45	0.11	12.5	1.1	0.88	0.14	20	5	323	264	103	105
HFHF	Low	6.9	0.7	0.59	0.09	12.0	1.1	0.72	0.04	17	4	541	232	192	89
	Medium	5.8	0.9	0.45	0.05	12.8	1.0	0.85	0.14	15	1	431	275	133	59
	High	5.3	0.9	0.42	0.07	13.0	0.6	0.85	0.05	26	9	207	121	62	14
	Mean	6.0	1.0	0.49	0.1	12.6	1.0	0.81	0.11	19	7	393	251	129	80

Soil organic carbon and nitrogen, physical status and biology in 2024

There were few differences in mean total C (%) between the three farmlets, but these values did consistently decrease with increasing slope (Table 2). Similarly, total N (%) decreased with increasing slope. Again, there were few differences in mean total N (%) between farmlets (Table 2). The C:N ratio in the topsoil averaged 13:1 across the three slope classes of the three farmlets. Bulk density increased with increasing slope, but there were otherwise no clear trends across the three farmlets (Table 2). Macroporosity values where higher on the high slope class (25%) compared to the other two slope classes (Table 2).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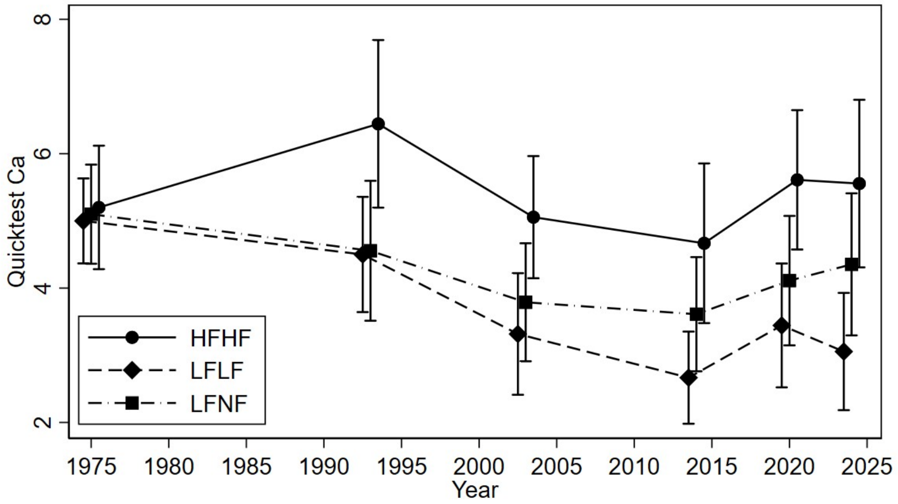
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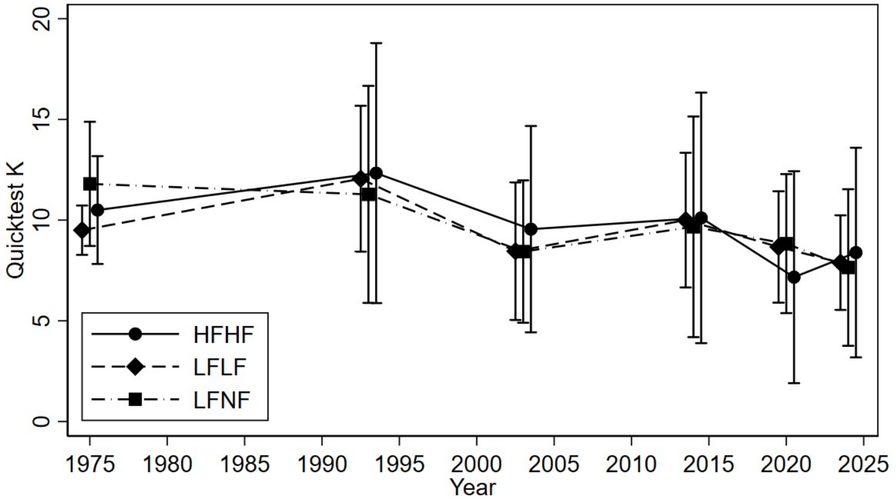
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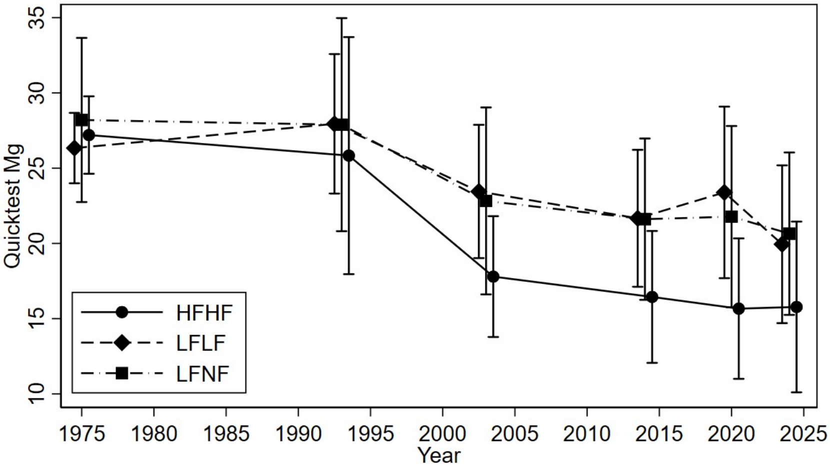

Figure 1 Mean soil pH and quick test calcium, potassium and magnesium in the 0-75 mm soil depth on the LFNF, LFLF and HFHF farmlets. The mean and standard deviation are for the 18 sites (threes slope classes x three aspects x 2 replicates)

Earthworm abundance increased by 47% from the LFNF to the LFLF farmlet and by 64% from the LFNF to the HFHF farmlets, while earthworm biomass increased 79% from the LFNF to LFLF farmlet and by 206% from the LFNF to the HFHF farmlet (Table 2). Averaged across the three farmlets, earthworm abundance and biomass on the medium slopes were only 71% and 64% of those found on low slopes, respectively. Averaged across the three farmlets earthworm abundance and biomass on high slopes were only 33% and 23%, respectively, of those found on low slopes.

Discussion

Soil pH averaged 4.8 across the three farmlets in 2024. This is a drop of 0.5 units since 2020. Prior to 2020, pH had shown very little change, averaging 5.3 (Figure 1). Edmeades et al. (1985) reported typical variation in soil pH test results in the order of 2-5% due to the sum of the variation in field sampling and laboratory analysis. Even after retesting all the soil samples, through the same laboratory, the change in pH still represents a decrease of more than 10% since the sampling in 2020. Furthermore, the decline in pH in 2024 has occurred across all three farmlets, despite the large difference in P inputs and associated legume and pasture growth between farmlets (Lambert et al. 1986). Pasture growth leads to the slow acidification of the soil, due to cation uptake exceeding anion uptake, causing the release of hydrogen ions from plant roots. Lime application to the farmlets has been limited to 1250 kg/ha and 2500 kg/ha in 1975 and 1979, respectively, and only applied on the HFHF. The limited use of lime on the experiment has been on the basis that field experiments conducted at the Research Station in the early 1970's found most of the pasture response to lime could be attributed to increased molybdenum (Mo) availability.

Molybdenum levels in legumes were still 0.2-0.5 ppm at the last assessment in 2020 (Data not presented). The recent drop in pH values needs to be explored in more depth in spring 2025 as a decrease in Mo availability, and an increase in aluminium and manganese toxicity risk may result from this pH drop.

This paper reports for the first time the long-term trends in Ca, Mg and K levels as influenced by long-term P fertiliser inputs and sheep grazing. Levels of Ca appear to be sustained in LFLF and HFHF through the addition of 25 and 75 kg Ca/ha/yr in the applications of 125 and 375 kg SSP/ha/yr to the LFLF and HFHF farmlets, respectively, along with the lime applications to the HFHF farmlet in 1975 and 1979. In contrast there has been a slow decline in Ca values from 6 to 3 MAF QT on the LFNF farmlet over ~50 years. Surprisingly, the actions of the grazing animal in returning a disproportionate amount of excreta back to low slope areas of the farmlets, has not depleted or increased Ca levels across slopes.

With no K and Mg applied as fertiliser throughout the study, both K and Mg values have slowly decreased over the last ~50 years. While there appears to be little influence of P fertiliser use and sheep grazing on the overall decline in K within each farmlet, there are some marked differences observed with slope. This effect varies by farmlet; while there is no difference in K values with slope on the LFNF farmlet, on the HFHF farmlet K values have decreased on the high slope class while increasing on low slope areas (Table 1). The K values for the soils on high slope areas on the HFHF are at the bottom end of the target ranges (5-8 MAF QT) at which a pasture response to K might occur, although the study by Morton et al. (2017), suggests any response would be small. The decline in Mg with increasing slope on the HFHF farmlet, like the decline in K, can probably be attributed to the impact of the grazing animal removing pasture from the high slope and returning excreta to low slopes areas. On the LFNF and LFLF farmlets it appears that mineral weathering rates are sufficient to offset any loss of Mg through transfer in dung to low slope areas. However, in the HFHF, Mg transfer to low slope areas is greater and not sustained by weathering (Table 1). While the Mg levels on the HFHF farmlet are below the optimum for livestock (20-25 MAF QT), they are still well above the levels where a pasture response would be expected (>10 MAF QT). The loss of base cations from the soils are associated with sulphate-sulphur leaching losses, which were found by Sakadevan et al. (1993) to be 10 times higher than nitrate in drainage water below the 250 mm soil depth on the LFNF and HFHF farmlets.

The Olsen P values on the HFHF farmlet reported here for 2024 appear to have declined (40 µg/ml) rather than continued to increase since results were last reported in 2016. At that time Olsen P averaged 50 µg/ml across the 18 permanent sites (three slope, three aspects, 2 replicates) on the HFHF farmlet (Mackay and Costall 2016). This decline is despite the fact the amount of P applied on the HFHF farmlet is more than 1.5 times maintenance P requirements. At this application rate Olsen P values should be increasing by more than 2 units each year in the 0-75 mm soil depth (Morton and Roberts 2024). Even allowing for variation due to field sampling and laboratory analysis, which can be in the order of 15-20% for the Olsen P soil test (Edmeades et al. 1985) the test values appear to be going in the wrong direction. Mackay and Costall (2016) suggested that the absence of any increase in Olsen P in the HFHF dating back to 2003 might be explained in part by the movement of P to soil depths below those traditionally sampled. They reported elevated Olsen P values in the 75 -150 mm in the HFHF farmlet.

The absence of any differences in soil organic carbon contents across the three farmlets, is consistent with previous findings that P fertiliser and sheep grazing history has had little impact on either soil organic matter content (Mackay et al. 2021b) or soil organic stocks to 300 mm (Mackay et al. 2021a; Bilotto et al. 2022). Condron et al. (2012) also reported few differences in soil organic carbon under varying P fertiliser and sheep grazing pastures at a different site. The differences in soil organic nitrogen contents between the LFLF and HFHF farmlets has narrowed since reported previously (Lambert et al. 2000). Bilotto et al. (2022) reported a decline in soil organic nitrogen stocks to 300 mm from 2003 to 2020 across all three farmlets. The decline in soil organic nitrogen is either the result of an increase in N losses, a reduction in biological N_2 fixation or a combination of both. It does help to explain the decline in measured pasture production and the necessity to reduce the sheep stocking rate on the HFHF farmlet in the last 20 years (Mackay et al. 2023). While there has been no clear trend in annual rainfall since the start of the study in 1975, the increase in mean daily temperature, has contributed to an increase ($p<0.01$) in the mean summer soil moisture deficit (January to March), which increased from 41 mm between 1982-88 to 55 mm between 2012-2018 (Mackay et al. 2022). Within the next 25 years atmospheric CO_2 concentrations are predicted to reach 550-750ppm (Feng et al. 2014), with further increases of 2 to 4°C in global temperature (IPCC 2023).

The absence of any differences in the physical condition (BD or macroporosity) of the soils between farmlets indicates increased sheep numbers with the application of P fertiliser has not resulted in soil compaction. This could have been offset by the increase in earthworm activity on the LFLF and HFHF farmlets, compared with the LFNF farmlet. While earthworm abundance in 2024 was on average within 10% of those measured in 2014 (Schon et al. 2019), overall there has been a decline in earthworm abundance from an average of 575 ind./m^{-2} in 1979 (Lambert 1986). This decline in earthworms is consistent with the decline in pasture production and sheep stocking rate, as Waters (1955) found a direct positive relationship between pasture production and the number and weight of the earthworms. This apparent declining trend warrants further investigation.

Conclusions

The P fertiliser and sheep grazing experiment established in 1975 allows us to examine long-term changes in soil fertility and biology, pasture ecology and animal production as influenced by P fertiliser and sheep grazing and under field conditions. It has become an invaluable field laboratory for in-depth experimental studies, for sense checking models and a resource for policy and industry. Over the decades, it has also been an important extension resource. If we are to fully understand the implications of variable inputs and management for permanent pasture systems within an increasingly rapidly changing climate, we must preserve such long-term field experiments.

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