

Terrain and soil texture confound land use comparisons of topsoil phosphorus in the middle hills of Nepal

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Abstract

Land-use comparisons of soil fertility are common in the Nepalese mid-hills, but they rarely test whether the land uses being compared occupy comparable terrain. We measured pH, organic matter, total nitrogen, available phosphorus and available potassium in thirty composite topsoil samples (0 to 20 cm) from adjacent agroforestry, cropland and community forest at Kankada in Makawanpur district, and recorded slope, aspect, altitude and texture class at every sampling point. Organic matter (3.23 to 3.29%), total nitrogen (0.072 to 0.092%), available potassium (203 to 265 kg ha⁻¹) and pH (5.72 to 5.79) were indistinguishable among the three land uses, with eta-squared at or below 0.04. Available phosphorus varied most, with geometric means of 75.7 kg ha⁻¹ under agroforestry, 47.9 under cropland and 20.0 under forest, but the three-way comparison was not significant (ANOVA on log-transformed values, $F(2,27) = 2.71$, $P = 0.085$), and with ten samples per group the design could detect only effects of eta-squared 0.26 or larger. Pooling the two cultivated land uses gave a threefold contrast against forest that was significant ($P = 0.039$), as did the national rating classes: twelve of twenty cultivated samples rated high in phosphorus against one of ten forest samples (Fisher exact test, $P = 0.017$). That contrast cannot be assigned to land use alone. Forest plots sat on steeper ground (27.6 against 18.7 and 19.4 degrees, $P < 0.001$) and coarser textures, and slope was negatively correlated with phosphorus across all samples.

1 Introduction

Trees have always been part of farmland. Roughly 43% of the world's agricultural land carries more than 10% tree cover [1], and where they grow, trees supply households with food, fuel, fodder and some protection for the land itself. Agroforestry, the deliberate combination of woody perennials with crops or livestock on the same unit of land [2], is common throughout Nepal's mid-hills, and the reasons are practical. Many hill soils are already depleted, mineral fertiliser is expensive and hard to carry up to the villages, and anything that keeps fertility on site therefore has value [3, 4].

The general case for agroforestry has strengthened. Pooling results from across the humid and sub-humid tropics, Muchane et al. [5] reported that agroforestry raised soil organic carbon by 21%, available nitrogen by 46% and available phosphorus by 11% relative to sole cropping. A more recent synthesis found that nitrogen-fixing trees lift soil carbon stocks by about 16%, and do so most strongly in warmer and drier places [6]. Studies from Nepal itself point the same way: comparing five land uses in Dhading district, Kharal et al. [7] found forest soils highest in organic matter and nitrogen and cereal-based cropland the poorest.

Comparisons of this kind share a design assumption that is seldom examined. They treat land use as the variable that separates the plots, and everything else as background. In hill Nepal that assumption is difficult to satisfy, because land use is not distributed at random across the landscape. Households clear and cultivate the gentler, deeper, more accessible ground and leave the steep, stony, shallow ground under forest. Any soil property that also varies with position on the hillslope will therefore differ between

land uses whether or not the land use itself has any effect. Phosphorus is a clear candidate, since it moves with eroding surface soil and is held differently in coarse and fine textures.

We set out to measure five standard fertility indicators under three adjacent land uses in one mid-hill village, and, unusually for this kind of study, to record the terrain and texture of every sampling point so that the assumption could be tested rather than asserted. We asked two questions. Do the five indicators differ among agriculture, agroforestry and forest? And are the land uses comparable in slope and texture, so that any difference found can reasonably be attributed to land use at all?

2 Materials and methods

2.1 Study area

The study was carried out at Kankada in Makawanpur district, in the mid-hills of central Nepal. The climate is subtropical monsoonal, with most rainfall between June and September. Sampling points were recorded on the national UTM grid and spanned 571158 to 573074 m easting and 3054705 to 3057984 m northing, an area of roughly 2 km by 3 km. Altitude was recorded at 21 of the 30 points and ranged from 294 to 522 m above sea level. Slopes ranged from 10 to 30 degrees and aspects from north through west to south-east.

The three land uses adjoin one another within the village. Agroforestry plots combine annual crops with planted and retained trees, chiefly *Melia azedarach* (bakaino), *Leucaena leucocephala* (ipil-ipil), *Ficus semicordata* (khanayo), *Bauhinia variegata* (tanki), *Terminalia alata* (saj) and *Diploknema butyracea* (chiuri), usually with banana and pineapple along field margins and terrace risers. Cropland is tilled conventionally and cropped with maize, rice, millet, mustard, black gram and horse gram. The community forest is dominated by *Shorea robusta* (sal) and *Schima wallichii* (chilaune), with *Castanopsis*, *Terminalia* and *Dalbergia* also present. Field notes recorded most forest sampling points as poorly managed, with sparse ground cover, stony surfaces and dry soil. Much of the present farmland was cleared from forest about fifteen years before sampling, and some households still practised shifting cultivation on parts of it.

2.2 Sampling design

Thirty composite topsoil samples were collected, ten from each land use. Each composite came from a separate landholding or forest compartment, so the ten replicates per land use are spatially independent rather than repeated points within a single field. At each point, five sub-samples were taken to 20 cm along a W-shaped traverse and combined in the field into one composite [8]. Slope, aspect, altitude and a description of the standing vegetation and current management were recorded at every point at the time of sampling. Input rates noted at the sampling points are expressed per katha (1 katha = 338 m²).

2.3 Laboratory analysis

Samples were analysed at the Regional Soil Testing Laboratory, Hetauda, Makawanpur, which operates under the Soil Management Directorate of the Department of Agriculture and is the laboratory used by comparable Nepali land-use studies [7]. The laboratory issued its report (reference 071/72, laboratory numbers 78 to 107) on 30 Poush 2071 in the Bikram Sambat calendar, corresponding to January 2015, so sampling was carried out in the preceding post-monsoon period.

pH was measured in a 1:2.5 soil-to-water suspension with a glass electrode. Organic matter was determined by wet oxidation [9] and total nitrogen by Kjeldahl digestion and distillation. Available phosphorus and available potassium were determined by the laboratory's standard procedures and are reported by it on an area basis in kg ha^{-1} . Texture was assigned to a class by the laboratory rather than reported as a particle-size distribution. The laboratory also supplied the national rating classes it applies, which we use in Section 3.5: pH acidic at or below 6.5, neutral 6.51 to 7.5, alkaline above 7.5; organic matter low at or below 2.5%, medium 2.51 to 5.0%, high above 5.0%; total nitrogen low at or below 0.10%, medium 0.11 to 0.20%, high above 0.20%; available phosphorus low at or below 30, medium 30.1 to 55, high above 55 kg ha^{-1} ; available potassium low at or below 110, medium 110.1 to 280, high above 280 kg ha^{-1} .

2.4 Data handling

Two records needed a decision before analysis, and we report both rather than adjust them silently. One forest sample (number 29) has organic matter recorded as 0.00%, which is not physically plausible for a forest topsoil; we treat it as missing in the organic matter analysis and report the result both ways. One forest sample (number 3) has pH recorded as 4.74 in the laboratory report and 7.74 in the compiled field worksheet; we use the laboratory value, since the report is the primary record and the transcription is not. The complete dataset of thirty samples is given in Supplementary Table S1.

2.5 Statistical analysis

Normality of residuals was assessed with the Shapiro-Wilk test and homogeneity of variance with the Brown-Forsythe form of Levene's test, and the omnibus test was then chosen to match. Where both assumptions held, we used one-way ANOVA. Where residuals were normal but variances unequal, we used the Alexander-Govern test [10]. Where residuals were not normal, we either transformed or used the Kruskal-Wallis test. Available phosphorus was strongly right-skewed (Shapiro-Wilk $P = 0.014$) and became well behaved on the natural-log scale (Shapiro-Wilk $P = 0.204$, Levene $P = 0.809$), so it was analysed after log transformation and means are reported back-transformed as geometric means. Post-hoc comparisons used Tukey's HSD, applied only where the omnibus test was significant or, where it was not, reported with their confidence intervals as descriptive quantities rather than as tests. Dunn's test with a Benjamini-Hochberg correction [11] was run as a distribution-free check. We report eta-squared as the effect size for every omnibus test, and a post-hoc power calculation establishing the smallest effect the design could detect at 80% power, so that the indicators showing no difference can be read quantitatively rather than dismissed. Significance was assessed at $\alpha = 0.05$ throughout, with no secondary threshold. One contrast, pooling the two cultivated land uses against forest, was decided

after inspecting the data and is reported as exploratory. Analyses were carried out in Python 3.13 using SciPy 1.17.

3 Results

3.1 The land uses do not occupy comparable terrain

Slope differed strongly among the three land uses (Table 1, Fig. 2a). Forest plots averaged 27.6 degrees against 18.7 for cropland and 19.4 for agroforestry, and the difference was the most significant result in the study ($F(2,27) = 12.05, P < 0.001$). Eight of the ten forest points sat at 26 degrees or steeper; no cropland point exceeded 22 degrees. Texture followed the same pattern. Both sandy loams in the dataset were forest points, and forest accounted for four of the ten loamy sands, so eight of ten forest samples were coarser than loam against four of ten cropland and two of ten agroforestry samples.

The design therefore does not isolate land use. Whatever separates forest soils from cultivated soils at this site, it includes a systematic difference in slope and texture as well as a difference in management.

Table 1
Terrain and texture of the sampling points by land use. Slope is mean $\pm$ standard deviation; texture rows give the number of samples in each class, $n = 10$ per land use.

Site variable	Cropland	Agroforestry	Forest	Test
Slope (degrees)	18.7 $\pm$ 3.5	19.4 $\pm$ 5.6	27.6 $\pm$ 4.2	$F(2,27) = 12.05, P < 0.001$
Slope range	12 to 22	10 to 30	20 to 30	n.a.
Loam	6	8	4	n.a.
Loamy sand	4	2	4	n.a.
Sandy loam	0	0	2	n.a.

3.2 Four of five indicators do not differ

Soil pH, organic matter, total nitrogen and available potassium were indistinguishable among the three land uses (Table 2, Fig. 1). Organic matter was almost identical, at 3.29, 3.23 and 3.24% under cropland, agroforestry and forest respectively, with an eta-squared of 0.000. Excluding the implausible zero raised the forest mean to $3.60 \pm 1.45\%$ and left the conclusion unchanged ($P = 0.776$). Total nitrogen was slightly higher under forest (0.092%) than under agroforestry (0.072%), but well within the scatter ($P = 0.701$, eta-squared 0.026). Potassium fell in the order cropland, agroforestry, forest, again not significantly ($P = 0.207$). All three land uses were mildly acidic and did not differ in pH ($P = 0.950$), although forest pH was far more variable (standard deviation 0.73, range 4.74 to 6.76) than agroforestry pH (0.22, range 5.37 to 6.13).

These are not demonstrations of equivalence. With ten samples per group the design had 80% power to detect only effects of Cohen’s f at or above 0.60, corresponding to eta-squared 0.264. Every observed

effect except phosphorus fell well below that threshold, so these four indicators are better described as untested at this sample size than as unchanged.

Table 2

Topsoil properties (0 to 20 cm) by land use, mean $\pm$ standard deviation, n = 10 per land use. The omnibus test differs by indicator according to which assumptions held: Alexander-Govern for pH, one-way ANOVA for organic matter and nitrogen, ANOVA on log-transformed values for phosphorus, Kruskal-Wallis for potassium.

Indicator	Cropland	Agroforestry	Forest	P	Eta-squared
pH	5.79 $\pm$ 0.36	5.75 $\pm$ 0.22	5.72 $\pm$ 0.73	0.950	0.003
Organic matter (%)	3.29 $\pm$ 1.12	3.23 $\pm$ 1.01	3.24 $\pm$ 1.78	0.996	0.000
Total N (%)	0.085 $\pm$ 0.048	0.072 $\pm$ 0.040	0.092 $\pm$ 0.068	0.701	0.026
Available P (kg ha ⁻¹)	94.3 $\pm$ 89.9	119.7 $\pm$ 104.9	37.2 $\pm$ 44.7	0.085	0.167
Available K (kg ha ⁻¹)	264.8 $\pm$ 110.5	245.1 $\pm$ 141.5	202.5 $\pm$ 144.7	0.207	0.041

3.3 Phosphorus varies most, but the three-way test is not significant

Available phosphorus showed the largest contrast and the largest effect size of any indicator, but the three-way comparison did not reach significance. Geometric means were 75.7 kg ha⁻¹ under agroforestry (95% CI 33.9 to 168.9), 47.9 under cropland (16.6 to 138.1) and 20.0 under forest (8.1 to 49.6). On the log scale, $F(2,27) = 2.71$, $P = 0.085$, eta-squared 0.167. The untransformed ANOVA gave $P = 0.098$ and Kruskal-Wallis gave $P = 0.110$. Within-group variability was extreme, with coefficients of variation of 88% under agroforestry, 95% under cropland and 120% under forest.

No pairwise comparison survived correction for multiple testing (Table 3). Agroforestry soils held 3.78 times the phosphorus of forest soils, the largest contrast in the dataset, with a Tukey-adjusted P of 0.075 and a confidence interval running from 0.90 to 15.94. Dunn's test with a Benjamini-Hochberg correction gave the same picture (adjusted $P = 0.112$ for that pair). The two cultivated land uses were indistinguishable from each other ($P = 0.713$).

Two secondary analyses did reach significance. Pooling agroforestry and cropland into a single cultivated class, decided after inspecting the data and reported here as exploratory, gave geometric means of 60.2 against 20.0 kg ha⁻¹, a threefold contrast (Welch $t = 2.22$, $P = 0.039$, Hedges $g = 0.83$; Mann-Whitney $P = 0.056$). The categorical national rating gave the same result without any distributional assumption: twelve of twenty cultivated samples rated high in phosphorus (above 55 kg ha⁻¹) against one of ten forest samples (Fisher exact test, $P = 0.017$; Fig. 1f).

Table 3

Pairwise contrasts in available phosphorus, from Tukey HSD on log-transformed values and back-transformed as ratios. The final row is the exploratory pooled contrast and comes from a Welch t-test.

Comparison	Ratio	95% confidence interval	P
Agroforestry / forest	3.78	0.90 to 15.94	0.075
Cropland / forest	2.39	0.57 to 10.08	0.307
Agroforestry / cropland	1.59	0.37 to 6.67	0.713
Cultivated / forest	3.00	1.06 to 8.50	0.039

3.4 Slope and texture track phosphorus

Across all thirty samples, slope was negatively correlated with available phosphorus (Spearman $r_s = -0.50$, $P = 0.005$; Fig. 2b). The correlation ran in the same direction within each land use, though no within-group correlation reached significance at these sample sizes (cropland $r_s = -0.47$, agroforestry -0.43 , forest -0.24). Texture followed suit: mean available phosphorus was 115.7 kg ha^{-1} on the eighteen loams, 37.6 on the ten loamy sands and 26.5 on the two sandy loams (Fig. 2c).

Because forest plots were both the steepest and the coarsest, slope, texture and land use are collinear in this dataset and cannot be separated with thirty samples. The threefold phosphorus contrast between cultivated land and forest is therefore consistent with at least three explanations that this design cannot distinguish: nutrient inputs to cultivated land, loss of phosphorus with eroding soil on steeper forest ground, and weaker retention in coarser forest textures.

3.5 Management records and rating classes

Management was noted at every sampling point at the time of sampling. On cropland, seven of the ten points carried a record of farmyard manure: five gave a rate of between 16 and 80 baskets per year and two recorded that none was applied. Three cropland points recorded mineral fertiliser, either urea or diammonium phosphate. Agroforestry points were described mainly by their tree and crop layout rather than by an input rate. No forest point recorded any input of any kind. Coupling livestock manure to cropland in this way is the foundation of hill farming in Nepal, where the animals supply the nutrients the crops depend on [12, 13], and these materials carry both inorganic and organic phosphorus into the topsoil [14].

These records do not support a simple dose relationship. Manure application, recorded at seven of the ten cropland points, did not correlate with available phosphorus (Spearman $r_s = 0.26$, $P = 0.58$) or with organic matter ($r_s = 0.38$, $P = 0.40$). The plot receiving 16 baskets per year had the highest phosphorus of any cropland sample, and one receiving 70 had among the lowest. At this sample size the recorded inputs explain none of the variation in phosphorus.

Against the national rating classes, phosphorus was the only indicator whose distribution differed materially between land uses (Table 4). Six of ten cropland and six of ten agroforestry samples rated high, against one of ten forest samples, while half the forest samples rated low. Nitrogen rated low in most samples under every land use, and potassium rated medium in most. Organic matter and total nitrogen were consistent with each other across the whole dataset ($r_s = 0.55$, $P = 0.002$), which supports the internal quality of the analytical results.

Table 4
Number of samples in each national rating class by land use, $n = 10$ per land use. Class boundaries are those applied by the Regional Soil Testing Laboratory and are given in Section 2.3.

Indicator	Class	Cropland	Agroforestry	Forest
Organic matter	low	3	4	4
	medium	6	6	4
	high	1	0	2
Total nitrogen	low	6	8	7
	medium	4	2	2
	high	0	0	1
Available P	low	4	2	5
	medium	0	2	4
	high	6	6	1
Available K	low	1	0	2
	medium	5	8	7
	high	4	2	1

4 Discussion

4.1 What this comparison can and cannot support

The result that would ordinarily be reported from a dataset like this one is that agroforestry soils hold more available phosphorus than adjacent forest soils. The contrast is large, close to fourfold, and it runs in the direction the meta-analytic literature predicts [5]. It is also not statistically significant. Under every test whose assumptions the data satisfy, and under a distribution-free check as well, the three-way comparison returns P between 0.075 and 0.112. The observed effect size, eta-squared 0.167, sits below the 0.264 that ten samples per group could reliably detect. A study of this size can describe the contrast; it cannot establish it.

We make that point explicitly because the alternative is common and misleading. An uncorrected pairwise test run after a non-significant omnibus test will return a smaller P value for the agroforestry and forest pair, and reporting it as the study's finding would overstate what thirty samples can show. The confidence interval is the more honest summary: agroforestry soils held somewhere between 0.9 and 16 times the phosphorus of forest soils. That interval is compatible with a large effect and also with none.

Where the data do support a conclusion is at the coarser contrast between cultivated and uncultivated land, which reaches significance both as a pooled comparison of means ($P = 0.039$) and, more robustly, in the categorical rating classes, where twelve of twenty cultivated samples rated high in phosphorus against one of ten forest samples ($P = 0.017$). The categorical result depends on no distributional assumption and uses the interpretation scale the laboratory itself applies, which makes it directly usable by extension staff. Cultivated topsoil at this site is better supplied with phosphorus than the adjacent community forest. Which of the two cultivated systems is better supplied, and by how much, this study cannot say.

4.2 Terrain is part of what land-use comparisons measure

The more useful finding is the one the design was built to test. Forest plots at Kankada sat on ground averaging nine degrees steeper than the cultivated plots, and both sandy loams in the dataset were forest points. Slope was negatively correlated with phosphorus across the whole sample. Since households clear the gentler and deeper ground and leave the steep and stony ground under trees, this is not an accident of our sampling but a feature of how mid-hill landscapes come to be arranged.

The mechanisms are well established. Phosphorus moves with eroding surface soil, and steeper slopes lose more of it; coarse-textured soils hold less exchangeable and organically bound phosphorus than loams [15, 16]. Field notes describing most forest points as poorly managed, with sparse ground cover and stony surfaces, fit that reading. So does the wide spread of forest pH, from 4.74 to 6.76, which suggests a more heterogeneous set of sites than the cultivated land rather than a uniform forest condition.

We are not arguing that management has no effect. Cultivated plots at this site received manure and the forest received nothing, and that difference is real. The point is narrower and harder to avoid: with land use, slope and texture collinear, a study of this design cannot apportion the phosphorus difference among them, and reporting the whole of it as a land-use effect would be an error. Comparisons of this kind in the mid-hills should record terrain and texture at every point and either match plots on them or model them as covariates. Neither is expensive. Both would change what these studies can claim.

4.3 Organic matter and nitrogen

Organic matter was effectively identical under all three land uses, which is worth stating plainly because it contradicts both the general expectation and an earlier reading of these data. Forest soils are usually the richest in organic matter, and were so in the comparable Dhading study [7], because tillage speeds up its breakdown while undisturbed forest retains and recycles it [15, 17]. Here the forest is degraded,

with sparse ground cover on steep and stony ground, and holds no more organic matter than tilled cropland. That is a statement about the condition of this community forest rather than about forest in general.

Agroforestry also failed to exceed cropland in organic matter or nitrogen, as the global averages would predict [5]. Age is the likeliest reason. These systems were established on land cleared from forest about fifteen years before sampling, and the shifting cultivation once practised there left a depleted base to build from. Carbon accumulation under agroforestry is slow and usually becomes detectable over decades. Species composition matters too: of the tree species recorded, only *Leucaena leucocephala* fixes nitrogen, so these systems capture little of the mechanism that drives carbon gains elsewhere [6]. Sampling to 20 cm will also have missed any change below the plough layer.

4.4 Limitations

The study covers one village, sampled once, at one depth, with ten composites per land use, and it is a space-for-time substitution rather than an experiment. Land uses were not randomly assigned, and Section 3.1 shows how far from balanced the resulting comparison is. Statistical power was sufficient only for large effects.

Three further limits deserve stating. The data were collected in 2014 and describe conditions at that time; management at the site may since have changed. Texture was assigned to a class by the laboratory rather than measured as a particle-size distribution, so the texture analysis in Section 3.4 rests on three ordered categories, with only two samples in the coarsest. And input rates were noted only as field observations at the sampling points, at seven of the thirty, so the management record is too sparse to test against the soil chemistry with any power.

What the study does offer is a fully documented baseline from a part of Nepal with few published soil datasets, with terrain, texture, vegetation and management recorded alongside the chemistry, and with the complete sample-level data published rather than summarised. Studies that want to test the land-use question properly here will need repeated sampling across matched terrain, several depths and more than one site.

5 Conclusion

At Kankada, topsoil organic matter, total nitrogen, available potassium and pH did not differ among agroforestry, cropland and adjacent community forest. Available phosphorus varied about fourfold between agroforestry and forest, but the three-way comparison was not significant and the study was underpowered for an effect of the size observed. Cultivated land as a whole did hold significantly more phosphorus than the forest, both as a pooled contrast and in the national rating classes.

That contrast cannot be assigned to land use alone. The forest plots were significantly steeper and coarser-textured than the cultivated plots, and slope was negatively correlated with phosphorus across the whole dataset, so terrain and management are confounded in a way thirty samples cannot separate.

For soil fertility work in the mid-hills the practical implication is a matter of design rather than of trees: record slope and texture at every sampling point, and either match plots on them or carry them as covariates. Without that, a landscape pattern is easily reported as a land-use effect.

Declarations

Competing interests

The authors declare that they have no competing interests.

Ethical approval

Not applicable. This study did not involve human participants, human material or human data. It reports chemical and physical measurements on thirty soil samples, together with observations of terrain, vegetation and land management recorded at each sampling point. No interviews, questionnaires or other procedures involving people were carried out, and no personal data of any kind were collected. Soil sampling on community forest land was carried out with the prior agreement of the community forest user group that manages it.

Consent to participate

Not applicable. The study involved no human participants.

Consent to publish

Not applicable. The manuscript contains no images, no identifiable personal data and no material relating to any identifiable individual.

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Author Contribution

P. Paswan designed the study, carried out the field sampling and household survey, coordinated the laboratory analysis, analysed the data and wrote the manuscript. B. H. Wagle and K. R. Acharya contributed to the study design and the interpretation of the results and revised the manuscript. All authors read and approved the final version.

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Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information (supplementary table s1).

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Figures

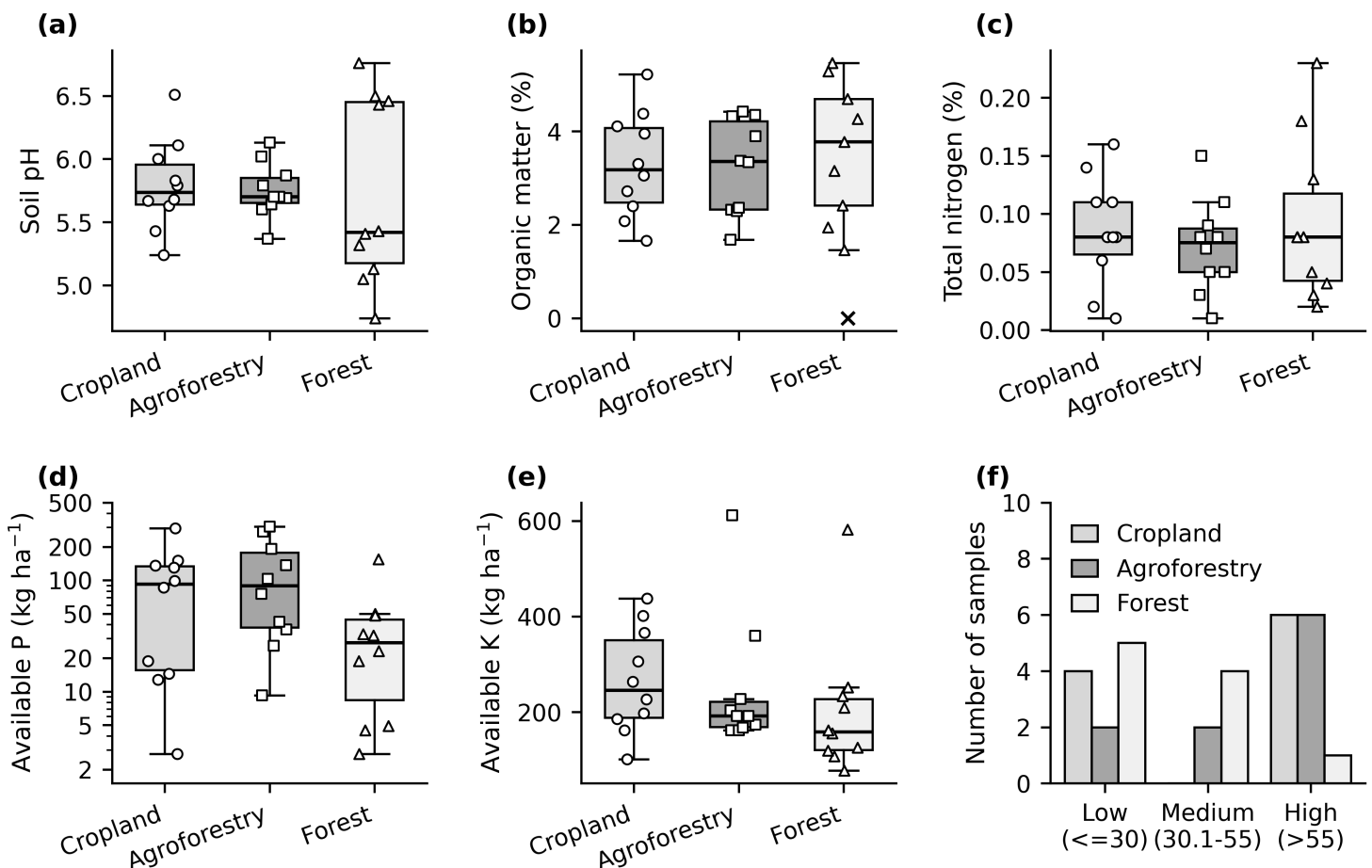


Figure 1

Topsoil properties by land use. (a) pH, (b) organic matter, (c) total nitrogen, (d) available phosphorus on a logarithmic scale, (e) available potassium, (f) number of samples in each national phosphorus rating

class. Boxes show the median and interquartile range, whiskers extend to 1.5 times the interquartile range, and all individual samples are plotted. The cross in panel (b) marks the forest sample recorded as 0.00% organic matter, which is excluded from that box.

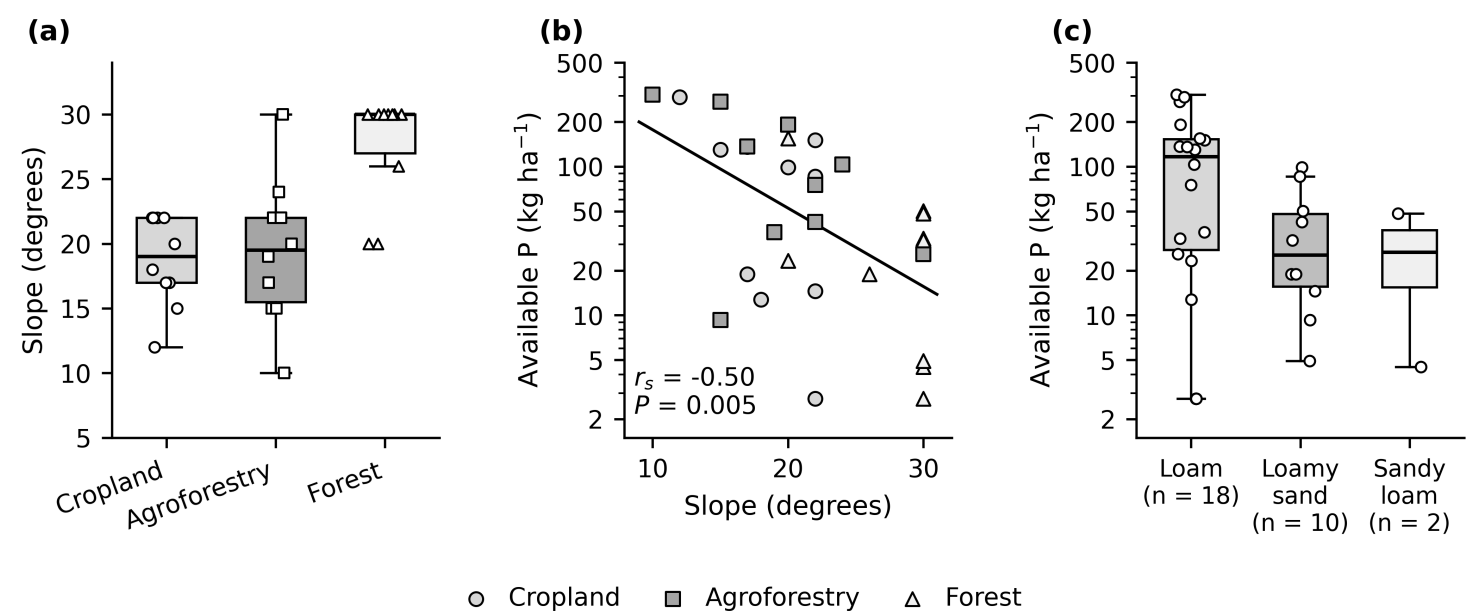


Figure 2

Terrain, texture and phosphorus. (a) Slope by land use. (b) Available phosphorus against slope for all thirty samples, with a fitted line on the log scale. (c) Available phosphorus by texture class.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryTableS1.xlsx](#)