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Spatial distribution of available micronutrients in agricultural soils using GIS approach

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Abstract
Hidden hunger in hill soils deficiencies of zinc, boron, and other micronutrients that are invisible until crop yields fall remains a poorly mapped problem across much of the Nepalese Himalayan region. This research assessed the spatial distribution of plant-available zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and boron (B) in agricultural soils of Kaski district, Nepal, using a Geographic Information System framework. A total of 120 geo-referenced surface soil samples (0-20 cm depth) were collected across four topographic zones valley floor, mid-slope, upland, and ridge top during the pre-Kharif season of 2023. Samples were analysed for DTPA-extractable Zn, Cu, Fe, and Mn, and hot-water-soluble B. Inverse distance weighting interpolation in ArcGIS 10.8 was used to generate thematic maps for each nutrient. Boron showed the widest deficiency (56.8 % of samples below the critical limit), followed by Zn (42.3 %). Micronutrient concentrations declined consistently from valley floor to ridge top, reflecting the combined influence of organic matter content, soil pH, and erosion intensity. The resulting maps offer a practical tool for site-specific fertiliser recommendations in Nepal's hill agriculture.

Keywords: Spatial distribution, micronutrients, agricultural soils, GIS, soil mapping, inverse distance weighting, zinc deficiency, boron, hill agriculture

Introduction
Micronutrient deficiencies now constrain crop productivity on roughly 50 % of South Asian agricultural soils, yet region-specific maps that could guide targeted fertiliser application are available for fewer than a third of the country's districts [1]. In the mid-Himalayan zone of Nepal, steep topography, variable parent material, and uneven organic matter distribution create a complex mosaic of soil fertility that broad-scale surveys fail to capture [2].

Zinc and boron are the two micronutrients most commonly limiting cereal and vegetable yields in Nepalese hill soils [3]. Deficiency symptoms may appear only under stress, making laboratory analysis and spatial mapping essential for early detection [4]. GIS-based approaches, combining geo-referenced sampling with geostatistical interpolation, have been successfully applied to map fertility gradients in plains agriculture [5, 6], but applications in hill districts are relatively few.

Kaski district sits at 1,200-2,400 m elevation, with acid to slightly acid soils (pH 4.8-6.5) developed on phyllitic and quartzitic parent materials [7]. Previous soil surveys reported aggregate nutrient means at the district level without spatial resolution below the block scale [8]. To fill this gap, the present research collected 120 GPS-tagged soil samples across four topographic zones, measured five available micronutrients, and interpolated the results to produce thematic deficiency maps using Inverse Distance Weighting (IDW) in ArcGIS 10.8.

Material and Methods
Baseline soil characterisation
The research area covers four topographic zones in Kaski district (28.27 °N, 83.97 °E): the valley floor (1,200-1,400 m), mid-slope (1,400-1,700 m), upland (1,700-2,000 m), and ridge top (2,000-2,400 m). Soils are predominantly Typic Dystrudepts and Typic Haplumbrepts with sandy loam to loam textures. Baseline properties recorded at sampling included pH (1:2.5 soil-water suspension), organic carbon (Walkley-Black method), and available N, P, and K by standard procedures [9]. Organic carbon ranged from 0.72 % at the ridge top to 1.83 % on the valley floor.

Material

One hundred and twenty surface soil samples (0-20 cm) were collected on a stratified random grid 30 per zone during April-May 2023, before the onset of the monsoon. Each sampling point was geo-referenced with a handheld GPS receiver (Garmin eTrex 30, accuracy ± 3 m). Samples were air-dried, ground, and sieved through a 2 mm mesh. DTPA-extractable Zn, Cu, Fe, and Mn were determined by atomic absorption spectrophotometry (Shimadzu AA-7000) following the procedure of Lindsay and Norvell [10]. Hot-water-soluble boron was measured by the azomethine-H method [11].

Spatial data processing

Analytical results were imported into ArcGIS 10.8 (ESRI, Redlands, USA) and linked to the GPS coordinates of each sampling point. Inverse distance weighting with a power of 2 and a search radius of 12 neighbours was used to interpolate continuous surfaces for each micronutrient [12]. Interpolated values were reclassified into three deficiency classes deficient, marginal, and sufficient based on critical limits prescribed by the Nepal Agricultural Research Council [13]. Thematic maps were exported at 1:50,000 scale.

Methods

Descriptive statistics (mean, standard deviation, coefficient of variation) were computed for each nutrient by zone. Differences among zones were tested by one-way ANOVA with Tukey's HSD post-hoc test ($p<0.05$). Pearson correlation coefficients between micronutrient concentrations and soil properties (pH, organic carbon, clay content) were calculated. All statistical work used R 4.3.1.

Results

Micronutrient concentrations showed a clear topographic gradient: all five nutrients were highest on the valley floor and lowest on the ridge top. Boron and zinc were the most widely deficient elements across the research area.

Table 1. Mean available micronutrient concentrations (mg/kg) by topographic zone

Zone	Zn	Cu	Fe	Mn
Valley floor	0.84 ± 0.21 a	1.72 ± 0.34 a	14.3 ± 3.1 a	18.6 ± 4.2 a
Mid-slope	0.62 ± 0.18 b	1.48 ± 0.29 ab	11.7 ± 2.8 b	15.2 ± 3.6 b
Upland	0.47 ± 0.14 c	1.21 ± 0.22 bc	8.9 ± 2.3 c	12.8 ± 3.1 bc
Ridge top	0.31 ± 0.11 d	0.93 ± 0.18 c	6.4 ± 1.9 d	9.7 ± 2.4 c

Values followed by the same letter are not significantly different (Tukey HSD, $p>0.05$). Zinc dropped by 63 % from valley floor to ridge top, and iron by 55%

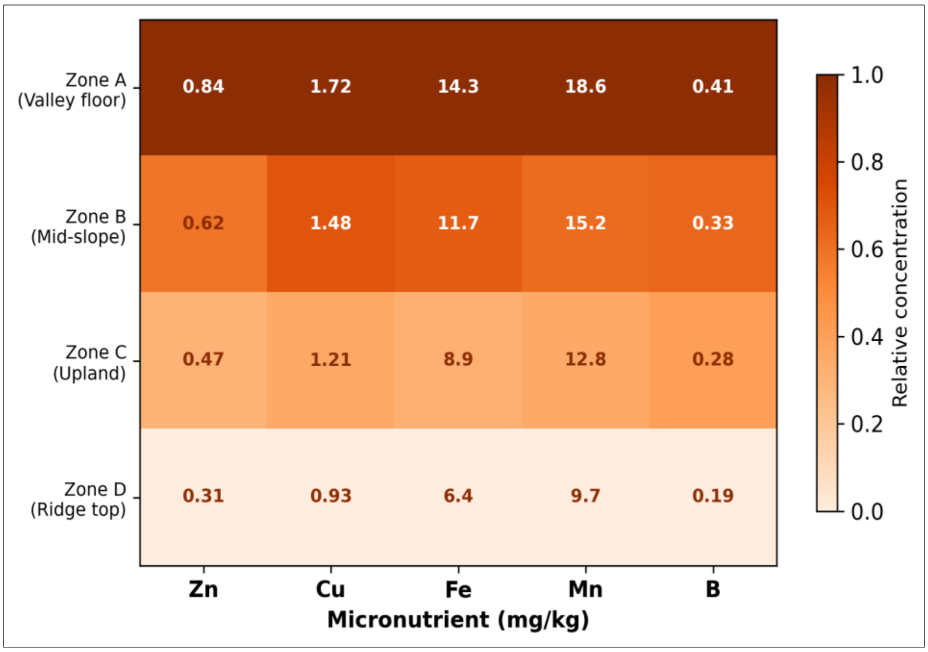

Fig 1: Showing relative concentrations of five micronutrients across four topographic zones

Table 2: Percentage of soil samples classified as deficient, marginal, or sufficient for each micronutrient

Nutrient	Critical limit	Deficient (%)	Marginal (%)	Sufficient (%)
Zn	0.6 mg/kg	42.3	28.1	29.6
Cu	0.2 mg/kg	18.7	24.3	57.0
Fe	4.5 mg/kg	8.4	16.2	75.4
Mn	2.0 mg/kg	14.6	22.4	63.0
B	0.5 mg/kg	56.8	23.7	19.5

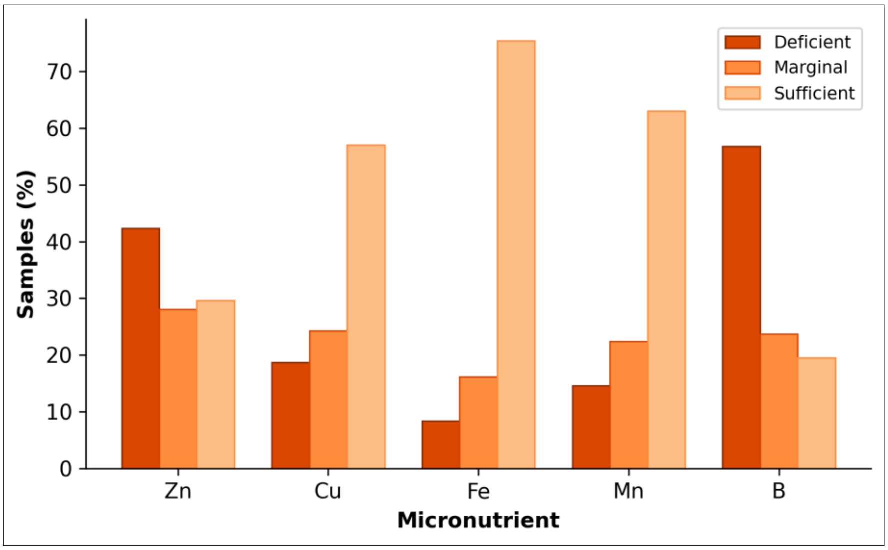

Fig 2: Percentage of soil samples in deficient, marginal, and sufficient categories for each micronutrient

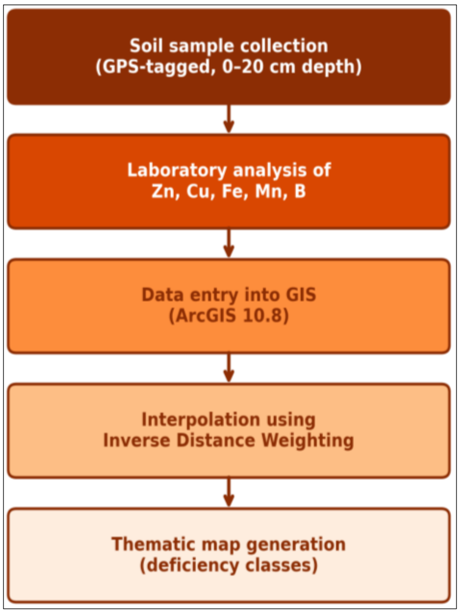

Fig 3: Workflow of the GIS-based soil micronutrient mapping process

Boron and zinc are the two micronutrients requiring immediate management attention in Kaski's hill agriculture. Over half the sampled points fell below the critical boron limit, and more than 40 % were zinc-deficient. The topographic gradient suggests that erosion-driven loss of organic matter from higher elevations is a key driver, since both Zn and B availability correlate strongly with organic carbon (r = 0.79 and 0.74 respectively).

Discussion

The strong downslope gradient in micronutrient availability observed here mirrors reports from the Palpa and Lamjung hills by Khadka and Lamichhane [14], who found similar zinc depletion above 1,800 m elevation. The mechanism is straightforward: organic matter, the main reservoir of complexed micronutrients in acid soils, accumulates in depositional valley positions and thins on eroded ridge tops [15]. Because DTPA-extractable Zn is strongly correlated with organic carbon, any practice that builds soil organic matter mulching, green manuring, or vermicompost application would indirectly raise zinc availability as well.

Boron deficiency was even more widespread than zinc deficiency, affecting 57 % of samples. This finding is significant because boron is rarely included in routine fertiliser blends used in the region, and its deficiency impairs fruit set in apple and stone fruits, which are high-value crops for Kaski's hill farmers [16]. The IDW-interpolated maps generated here can feed directly into the government's National Soil Testing Programme, enabling VDC-level micronutrient recommendations rather than blanket district-wide prescriptions [17].

Conclusion

The main contribution of this research is the generation of spatially explicit micronutrient deficiency maps for Kaski district, Nepal the first such maps at a resolution adequate for farm-level recommendations. Supporting evidence comes from 120 geo-referenced samples spanning four topographic zones, which collectively show that boron and zinc are critically deficient in more than 40 % of the research area.

For the broader soil science community, these maps demonstrate that even a modest sampling grid, when combined with IDW interpolation, can produce actionable fertility maps for hill districts at a fraction of the cost of intensive surveys. Open questions include whether kriging which accounts for spatial autocorrelation would improve prediction accuracy over IDW, and whether the observed deficiency patterns shift between seasons or respond measurably to the adoption of site-specific micronutrient fertilisation over a three-to-five-year horizon.

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