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Land-Use Change Along Altitudinal Gradients in Mountain Ecosystem of Eastern Himalaya (Northeast India): *Effect on Plant-Available Soil Micronutrients*

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Abstract

Management of soil micronutrients for better crop produce needs sound understanding of their status and causes of variability. This is more relevant for acid soils developed in the mountain ecosystem of Eastern Himalaya (Northeast India). We assessed the status, and the effect of land use systems along wide altitudinal gradients (14 m to 4090 m masl) on soil properties and plant available micronutrient concentrations (DTPA extractable Fe, Mn, Cu and Zn) across the region. Soils of the region varied widely in micronutrient concentrations: Fe from 0.665 to 257.1 mg kg^{-1} while Mn, Cu and Zn from traces to 93.4, 17.1 and 34.2 mg kg^{-1}, respectively. On conversion of evergreen forests (EF) to upland agriculture (Shifting-SC and Settled-SA) and plantation (PH), Mn, Cu and Zn concentrations decreased significantly (p <0.05) from 30.5, 1.74 and 2.13 mg kg^{-1} to 6.44-17.8, 0.68-0.81 and 1.06-1.42 mg kg^{-1}, respectively. Grass land (GL) recorded the highest Zn concentration (3.0 mg kg^{-1}) while Mn (24.9 mg kg^{-1}) and Cu (1.16 mg kg^{-1}) concentrations were comparable with lowland paddy agriculture (LP) but higher than upland agriculture. Degradation of EF to scrub land (SL) recorded the lowest Mn (5.91 mg kg^{-1}), Cu (0.59 mg kg^{-1}), and Zn (0.68 mg kg^{-1}) concentrations. The Fe concentration was however, comparable among EF, GL, LP and SC (40.1-52.2 mg kg^{-1}) but increased in degraded SL (+73%) over EF (48.7 mg kg^{-1}). Micronutrient concentrations among the land uses were inconsistent and followed the order: (i) Fe: SL>PH>LP>EF>GL>SC>SA, (ii) Mn: EF> GL> LP> PH> SC> SA>SL; (iii) Cu: EF>GL>LP>SC>SA=PH>SL; and (iv) GL>EF>LP>SC>SA>PH>SL. Four micronutrients responded differently and followed a non-linear, 6th – order polynomial trend along the altitudinal gradients (<500 m to 4100 m masl). Peak concentrations of Fe, Mn, and Cu were recorded at 1001-2000 m elevation while Zn was recorded at > 4000 m masl. Altitude mediated positive influence on soil properties including micronutrient concentrations were observed only in non-cultivated land uses (EF and GL) with an exception to lowland agriculture. Three key soil properties namely pH, clay and organic carbon contents contributed significant variation (54-64%) in micronutrients in the soils of the region.

1. Introduction

Soil micronutrients namely iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn), though required in small quantities, yet play an essential role for maintaining balanced crop growth and completion of crop life cycles (Hänsch and Mendel, 2009). Low micronutrient availability in soils may lead to sub-optimal plant productivity as well as poor quality of the produce. Plant availability of soil micronutrients is influenced by many factors such as land use change, soil management, cropping system practices etc. (Dessalegn et al., 2014; Shukla et al., 2014). Soil properties such as pH, clay content, organic matter, and other nutrients also significantly influences soil micronutrient availability (Li et al., 2007; Najafi-Ghiri et al., 2013; Rengel, 2015). Solubility of micronutrients in soils is again regulated by several competing reactions such as sorption, precipitation and even chelate formation. Thus, from agricultural point of view, ‘plant available’ form is more important than total content of micronutrients in soil (Marschner, 1995).

Northeast India (NEI) is a unique ecosystem in the world, with undulating landscape extends from < 10 m to beyond 7800 m elevation from mean sea level (masl). Setting in the high rainfall, fragile hilly (> 77% GA: geographical area of 26.2 M ha) ecosystem of eastern Himalaya (EH), the region is known for its richness in biodiversity, forest covers (in 62% GA) and phytomass (Choudhury et al., 2013, 2016; NRSC, 2019). Despite significant forest cover, NEI is also highly vulnerable to land degradation attributed to faulty land use practices, strong soil acidity (> 53% GA) and water erosion (> 23% GA). Over the past few decades, deforestation in the form of burning of vegetation due to prevalence of shifting cultivation (SC), cultivation along the steep slopes in uplands (bun and terrace agriculture), extensive open cast coal mining etc. converted significant forest areas to degraded scrub land (> 11% GA). This resulted in colossal loss of phytomass and vegetative cover while increased the severity of erosion and soil losses many folds (10 t/ha to 155 t/ha) in undulating uplands (Satpathy et al., 2003; Dabral et al., 2008; Maji et al., 2010; Choudhury et al., 2013). Soils of

the region mostly developed from acidic parent materials of shale and sandstone origin in hills while alluvium deposits in the intermountain valleys. Over the years, attention was given on acid soil amelioration through liming, and inorganic fertilization with special emphasizes to address P-deficiency while management of micronutrients was almost ignored. As a result, micronutrient deficiency has equally become a major factor of productivity constraints to most of the crops grown in the region. Presently, > 35% soils of the region are deficient in DTPA-extractable Zn, and so as Cu in 1.88% followed Mn in 1.66% and Fe in 1% area (Kumar et al., 2016; Shukla and Behera, 2019).

Land use land cover change (LULC) often causes alterations of soil properties (Dessalegn et al., 2014; Cade-Menun et al., 2017) and so, thus, accumulation and plant availability in micronutrients (Yeshaneh, 2015; Onwudike et al., 2016). Such large-scale transformation of forests to agriculture (shifting and settled) and plantation, forests and agriculture to scrub land in NEI is expected to influence micronutrient availability as well. Previous studies reported land use and altitudinal variation mediated significant changes in soil organic carbon (SOC: 0.5–5.5%) in the region (Choudhury et al., 2013, 2016). Since SOC pool is the primary source of plant nutrition to support marginal input-intensive rainfed agricultural production system of the region, therefore, the concentration of plant-available micronutrients is also expected to vary with land use and altitude mediated changes in soil properties, climate (rainfall, temperature), and vegetation (Choudhury et al., 2016). However, the region still lacks detailed information on complex interaction of acidity, soil properties and interaction of LULC and altitudinal gradient on micronutrient's availability in this vast (> 26 M ha area) hill ecosystem of Eastern Himalaya. This has become major bottleneck for devising location-specific micronutrient management strategies for improvement of crop productivity and quality of the produces while restoring degraded scrub lands.

Therefore, in the present study, an attempt was made to answer the following key questions:

i. What is the status of plant available micronutrient (DTAP extractable Fe, Mn, Cu, and Zn) concentrations in the soils of Northeast India;
ii. What is the impact of land use change on plant available micronutrient concentrations;
iii. How strongly does the altitudinal variation influence the micronutrient concentrations among and across the land uses;

2. Materials And Methods

2.1. Study area- location, climate and soil

The study area represents North-east India (NEI), lies from 21.57° N to 29.26° N latitude and 87.50° E to 97.30° E longitude with a geographical area (GA) of 26.2 million ha in the fragile Eastern Himalayan (EH) landscape (Fig. 1). Nearly 77% of the region is hilly with steep slopes along an altitudinal gradient extending from < 10 m (at South Garo Hills, Meghalaya) to above 7800 m masl (at Sikkim Himalaya). The varied physiographical features and altitudinal differences in the region give rise to varied types of climate ranging from hot humid to temperate and alpine. Annual average rainfall exceeds 2000 mm with wide orography led spatial variability (1500–11500 mm) (Prokop and Walanus 2014). The region experiences hot summer and cold winter with temperature varying from sub-zero (during winter) in Sikkim Himalaya to 38° C in the plains (Tripura) (Choudhury et al., 2016).

Soils of the region were mostly developed from the transported materials of shale, sandstone and recent alluvium deposits. In the central plain including Brahmaputra valley (Assam), alluvium derived deep medium textured soils (loamy) dominate while in the vast hilly region and sloppy uplands (> 77% GA), soils developed from shale and sand stone are red and lateritic with very shallow (in steep slopes) to medium in depth and relatively fine in texture. Soils are invariably acidic in reaction, with half of them (53% of GA) are very strong to strong in reaction (pH: 4.5–5.5). Complex

interaction of geographic location, high rainfall and conducive temperature favours luxurious phytomass production which in turn adds higher organic carbon (98% GA with > 1% SOC) in the soils of the region (Choudhury et al., 2013).

2.2. Sampling strategy: selection of sampling locations across land use systems

The LULC map at 1: 50000 scales of the study area (Fig. 1) was sourced from the Bhuvan web mapping service of National Remote Sensing Centre, originally derived from multi-season Resourcesat-2 ortho-rectified LISS-III satellite data of 2015-16 (NRSC, 2019). Nearly 62.5% GA is under different types of forest covers (e.g. Evergreen / semi-evergreen / deciduous /forest plantation) and half (30.7% GA) of them is evergreen in nature (EF). EF is native forests dominated by subtropical pine (eg. *Pinus spp.*), broad-leaved forest (*Castanopsis indica* Roxb., *Quercus serrata* Murray., *Michelia oblonga* Wall etc.) and Tropical wet semi-evergreen forest (eg. *Shorea robusta* Gaertn. f., *Mesua ferrea* Linn etc.). Deforestation (from jhum, bun agriculture, coal mining etc.) transformed significant forest areas (> 11% GA) to scrub land (SL). The area under settled agriculture (SA) in upland, lowland paddy (LP) and current fallow occupies 16.2% GA. The agricultural crops in SA are mostly dry-seeded rice, maize, turmeric, ginger etc. and occupies 2.81% GA while in LP, puddled transplanted rice-fallow system is practiced in 13.38% GA. Shifting cultivation (SC, jhum) is practiced in 1.20% GA (excluding abandon jhum area) along the steep slopes of uplands, which were previously forests and currently under the cultivation of multiple agricultural crops (rice, maize, tapioca, yam, turmeric and ginger). Grass land (GL) in 3.3% GA (Table 1) spread across alpine to tropical regions and are dominated by wild grass species like *Setaria sphacelata* Moss., *Panicum maximum* Jacq., and *Thysanolaena maxima* Roxb. with scattered trees / shrubs like *Eupatorium odoratum* Linn., *Ageratum conyzoides* L. etc. (Choudhury et al., 2016). Plantation and horticulture (PH) occupies 2.04% GA with the dominance of tea, rubber, coconut, areca nut, pineapple citrus fruits and other unmanaged fruit orchards.

Table 1
Information on percent area, sampling numbers, agro-physical variables and measured soil properties (Mean ± SE) under major land use systems sampled across the study area (NER of India)

LULC*	SC	SA	LP	EF	GL	SL	PH
% of TGA[&]	1.20	2.81	13.38	30.68	3.28	11.18	2.03
No. of samples	83	90	98	96	70	93	70
Temperature/ °C	20.7 ± 0.23 (16.5–24.7[#]) [$]	21.5 ± 0.18 (19.5–25.3)	22.9 ± 0.20 (16.5–**27.4**)	18.2 ± 0.54 (7.0-25.74)	16.6 ± 1.21 (**0.8**–25.2)	21.0 ± 0.25 (10.5–25.7)	22.4 ± 0.38 (10.5–26.7)
Rainfall/ mm	2916 ± 17.3 (1200–3850)	2459 ± 5.9 (2100–3500)	2448 ± 63.8 (1280–3500)	2947 ± 25.9 (1234–3603)	2815 ± 57.9 (2200–4800)	2998 ± 150.3 (1635–11276)	2733 ± 172.7 (1280–**11351**)
Altitude/ m	1140 ± 75.6 (931–1809)	1017 ± 6.8 (230–1786)	870 ± 63.3 (20-2000)	1274 ± 21.4 (440–2024)	1742 ± 116.3 (788–**4100**)	1358 ± 23.1 (1000–1748)	850 ± 90.6 (14-1800)
Soil Order	Ultisol > Inceptisol	Inceptisol > Ultisol	Ultisol > Alfisol > Inceptisol	Ultisol > Inceptisol > Entisol	Ultisol > Inceptisol > Entisol	Ultisol > Inceptisol	Inceptisol > Ultisol > Entisol

*LULC: Treatment abbreviations are explained in text; [#], [$]: Figures in parenthesis are range of distribution; [#] [&]TGA = Total geographical area (TGA: 26.22 million ha)

From the map, we identified seven major land use systems dominant in the region and they are as follows (i) shifting cultivation (SC: current 0-1-year-old); (ii) settled agriculture (SA) in upland; (iii) lowland paddy-fallow agriculture (LP); (iv) Natural forest (EF: evergreen / semi-evergreen); (v) Grassland (GL); (vi) scrub land (SL: including scrub forests, coal mine degraded forests, abandoned degraded jhum); and (vii) plantation and horticulture (PH) in sloppy uplands. A total of six hundred (600) sampling locations were identified randomly and from each location, a composite of three surface soils (0–15 cm depth) were collected during the post-monsoon rainless dry season (January to April) across the seven land uses along the altitudinal gradients (14 to 4010 m masl) (Table 1). Distribution of samples across land uses with detailed description of agro-physical and soil properties analyzed (LULC, percent GA, rainfall, temperature, altitude, particle size distribution, soil organic carbon - SOC content etc.) under each land use is presented in Table 1.

2.3. Soil analysis

The collected soil samples were air-dried, and ground to pass through 2.0 and 0·5-mm sieves. Samples sieved through 2.0-mm sieve were used for soil textural analysis using International Pipette Method (Piper, 1966) while 0·5 mm sieved samples were analyzed for SOC estimation by Walkley and Black method (Nelson and Sommers, 1982). Soil pH, cation exchange capacity (CEC) and available macronutrients were determined following standard procedures (Jackson, 1973). The micronutrient estimation was done following Lindsay and Norvell (1978) method. Twenty milliliters of 0.005 mol L^{-1} DTPA (Diethylene triamine pentaacetic acid) + 0.1 mol L^{-1} TEA (triethanolamine) + 0.01 mol L^{-1} $CaCl_2$ (at pH ~ 7.30) were added to 10 g soil. The solutions were shaken for two hours at room temperature, centrifuged, and filtered through Whatman No. 42 filter paper. Clear aliquots were then analyzed for DTPA extractable micronutrient (Fe,

Mn, Zn and Cu) contents using atomic absorption spectrophotometer (Model Perkin Elmer AAnalyst 200) (Tables 2 and 3).

Table 2
Soil properties measured across landuses in the NEI.

LULC*	Sand/ %	Silt/ %	Clay/ %	SOC/ %	pH
SC	56.9a# ± 1.05 (23.8)*	17.8b ± 1.04 (33.8)	25.3b ± 0.84 (24.8)	1.73b ± 0.10 (32.7)	4.49b ± 0.08 (13.3)
SA	59.9a ± 0.40 (22.8)	13.9c ± 0.34 (28.9)	26.2 b ± 0.43 (19.1)	1.59b ± 0.04 (27.2)	4.43b ± 0.04 (12.2)
LP	43.4c ± 1.06 (23.6)	21.2a ± 0.46 (20.9)	35.4ab ± 0.99 (27.2)	2.39a ± 0.11 (32.8)	4.94a ± 0.09 (9.3)
EF	39.9 cd ± 2.08 (24.7)	24.7a ± 1.37 (30.0)	35.4ab ± 1.53 (31.2)	2.10a ± 0.12 (33.8)	4.60b ± 0.04 (14.1)
GL	42.5c ± 1.98 (24.9)	18.2b ± 1.42 (24.7)	39.2a ± 2.86 (51.5)	2.26a ± 0.15 (34.3)	4.93a ± 0.09 (6.0)
SL	60.8a ± 1.17 (37.6)	17.5b ± 0.67 (35.4)	21.7b ± 0.73 (30.9)	1.30c ± 0.08 (34.6)	4.10c ± 0.07 (20.0)
PH	51.6b ± 1.84 (27.2)	22.1a ± 0.46 (20.8)	26.2 b ± 1.08 (31.2)	1.22c ± 0.08 (29.7)	4.20c ± 0.05 (11.7)

#: Means in the column followed by different letters (a-d) are statistically significant at $p < 0.05$. *Figures in parenthesis are coefficient of variations (CV) in %.

Table 3
Measured DTPA-extractable micronutrient contents (without outliers) under major land use systems in the soils of NEI.

Land uses	DTPA-Fe	DTPA-Mn	DTPA-Cu	DTPA-Zn
	(mg kg^{-1})			
Shifting cultivation (SC)	40.17(± 3.46)bc*	13.35(± 1.63)c	0.81 (± 0.07)c	1.42(± 0.11)bc
Upland agriculture (SA)	35.0(± 1.70)c	6.44(± 0.26)d	0.68 (± 0.03)cd	1.25 (± 0.09)bc
Lowland paddy (LP)	52.26 (± 3.24)b	23.79 (± 0.72)b	1.03 (± 0.05)bc	1.63 (± 0.05)bc
Evergreen forest (EF)	48.71(± 4.31)bc	30.46 (± 2.02)a	1.74 (± 0.06)a	2.13 (± 0.13)b
Grassland (GL)	48.33 (± 2.63)bc	24.91(± 2.14)b	1.16 (± 0.07)b	3.01 (± 0.10)a
Scrub land (SL)	84.27 (± 4.61)a	5.91 (± 0.42)d	0.59 (± 0.04)d	0.68 (± 0.08)d
Plantation and Horticulture (PH)	76.11 (± 4.48)a	17.80 (± 0.54)c	0.68(± 0.05)cd	1.06(± 0.043)c
Over all of the region	58.76 (± 1.72)	20.37 (± 0.753)	1.09 (± 0.045)	1.78 (± 0.115)
*Means in the column followed by different letters (a-d) are statistically significant at 5% level of significance				

2.4. Statistical Analysis

Prior to factor analysis, data on DTPA-extractable micronutrients (Table 1) were checked for normal distribution. Analysis of variance was performed using PROC GLM procedure of SAS Version 9·2 to determine the statistical significance of land use effects on micronutrient concentrations. Pearson's correlation coefficient was used to determine the strength of relationship among the land uses, soil properties and altitudinal variations. The Duncan's multiple range test was done to test the significance of differences between means at p-value < 0·05. To reveal the likely causes of the evident differences in micronutrient concentrations among the land uses, we computed Pearson correlation coefficients between each of DTPA-extractable micronutrients Fe (Y1), Mn (Y2), Cu (Y3), and Zn (Y4) and the agro-physical parameters (including soil properties). Several of the correlations appeared to be strong, and to rank them in order of importance, we did step wise multiple regressions of Y1, Y2, Y3 and Y4 as response variables on the agro-physical and soil parameters (including macro nutrients-NPK) as predictors. We judged the predictors significant if the probability that their contributions were null was < 0.05, i.e. (p < 0.05 of the null hypothesis).

3. Results

3.1. Agro-physical variables and soil properties in the study area

Altitudinal variations in the sampling locations ranged from 14 m (in Garo Hills, Meghalaya) to over 4000 m masl (in Sikkim Himalaya). Mean elevation across land uses ranged between 850 m to1742 m masl. In uplands, elevations ranged from 230–1786 m in SA, 931–1809 m in SC and 14–1800 m from masl in PH. In LP, elevation ranged from 20-2000 m masl while EF extended from 440–2024 m masl. Scrub lands (SL) were mostly confined with 1000–1748 m masl while grass land (GL) extended from 788 m to > 4000 m masl in high land Sikkim Himalaya (Table 1). Mean annual temperature varied widely from 0.8° C in high - altitude (> 4000 m, Sikkim) GL to 27.4° C in low altitude LP (< 40 m, Assam). Similarly, annual rainfall also varied from 1200 mm (in Nagaland) to 11351 mm in Cherrapunji Plateau (Meghalaya). Mean annual rainfall among the land uses were above 2400 mm while mean annual temperature ranged from 16.6° C to 22.9° C (Table 1).

Soil particle size distribution (PSD: sand, silt and clay) varied widely (coefficient of variation, CV: 19.1–54.7%) across the study area (Table 2). Coarser fractions (sand) were dominant (> 50–60.8%) in SL, SA, SC and PH while finer fractions (silt plus clay, 56.6–61.1%) dominated PSD in EF, GL and LP. Among the land uses, EF, GL and LP had significantly ($p < 0.05$) higher clay contents (> 35–39.2%) while SL, SA and SC had significantly higher sand contents (56.9–60.8%). Soils were high in mean SOC content (1.22% in PH to 2.26% in GL) but varied widely (CV: 27.2–54.6%) across land uses. Average SOC content was significantly ($p < 0.05$) higher in GL, EF and LP (> 2.0%) than the other land uses. Invariably, soils of the studied region were moderate to strongly acidic in reaction (pH: 3.05 to 6.43) with low intensity variation (CV < 25%) but more acidified under SL and PH (pH: 4.10–4.20) than other land uses (Table 2).

3.2. Effect of land uses on micronutrient concentrations

The DTPA-extractable Fe concentration across the study area varied from 0.665 to 257.1 mg kg^{-1} while Mn, Cu, and Zn concentrations varied from traces to 93.4, 17.1 and 34.2 mg kg^{-1}, respectively. Mean Fe, Mn, Cu and Zn concentrations were 58.76, 20.37, 1.09, and 1.78 mg kg^{-1}, respectively. Effect of land use changes on micronutrient concentration was significant ($p < 0.05$) in the studied soil (Table 3). Soils under non-cultivated EF and GL had comparable mean Fe concentration (48.3–48.7 mg kg^{-1}). On cultivation in uplands (SC and SA), mean Fe concentration decreased (-17.7 to -28.1%) while cultivation in LP had comparable concentration with EF. However, on degradation of EF to scrub lands (SL), Fe concentration increased (+ 73%) and recorded the highest (Fe: 84.3 mg kg^{-1}). Similarly, plantation (PH) in sloppy uplands had 56.2% higher Fe concentration than EF. However, EF recorded the highest Mn (30.5 mg kg^{-1}) and Cu (1.74 mg kg^{-1}) concentrations followed by GL. Conversion of forests to agriculture (SC and SA) and plantations (PH) in uplands significantly ($p < 0.05$) reduced the Mn (− 41.5 to -78.8%) and Cu (-53.4 to − 60.9) concentrations while in lowland (LP), the reduction in Mn (-21.8%) and Cu (− 40.8%) over EF was relatively less. On degradation of EF to SL, concentrations of Mn and Cu further decreased and recorded the lowest among all the seven land uses. The mean Zn concentration was significantly ($p < 0.05$) higher in non-cultivated GL (3. mg kg^{-1}) and EF (2.13 mg kg^{-1}) than cultivated land uses (SC, SA, LP and PH). The reduction in Zn concentration was more in PH (-50%) and agriculture (SC and SA) in uplands (-33 to -41%) than lowlands (− 23.5%) over EF. Scrub land recorded the lowest mean Zn concentration, 68% less than EF. In upland agriculture, SC had higher concentrations of all four micronutrients than SA (Table 3; Fig. 2).

3.3 Response of micronutrients to land use changes along altitudinal gradients

The micronutrient concentrations (DTPA-Fe, Mn, Cu and Zn) varied widely across the elevation ranges with differential trends among the land uses (Figs. 3–4). In shifting agriculture (SC), with increase in elevation (931–1809 m masl), only Fe and Mn concentrations increased significantly ($p < 0.005$, r = + 486 to + 0.534) (Table 4) but not Cu and Zn concentrations (Figs. 3–4, Table 4). In settled agriculture (SA), all the four micronutrients did not have any significant trends along the altitudinal gradient of 230–1786 m masl. Unlike SA in uplands, Fe, Mn and Cu increased significantly ($p < 0.05$-0.0005, r = + 0.290 to + 0.517) in PH along the altitudinal gradient (14 to 1800 m masl). In SL, distribution of Fe was scattered and did not follow any trend (Fig. 3) while Mn, Cu, and Zn concentrations rather decreased with the increase in elevation from 1000–1800 m masl (Fig. 4, Table 4). However, in non-cultivated EF and GL, concentration of all the four micronutrients (Fe, Mn, Cu, and Zn) increased significantly ($p < 0.0005$, r = + 0.557 to + 0.795) with the increase in elevations ranged from 440–2024 m and 788–4100 m masl, respectively. Low land paddy agriculture (LP) was an exception where alike EF and GL, all the four micronutrients increased significantly ($p < 0.0005$, r = + 0.604 to 0.770) with the increase in elevations ranged from 20–2000 m masl (Figs. 3–4; Tables 1 and 4).

Table 4
Response of land use systems to altitudinal gradients measured in terms of correlation coefficients (r) on particle size distribution (%), SOC (%) and DTPA-extractable micronutrient contents (mg kg− 1)

Altitude	Correlation coefficient values (r) with altitudinal gradients						
vs.	SC	SA	DF	GL	SL	PH	LP
Sand /%	0.030	-0.190	-0.138	-0.461	0.248*	0.103	-0.413
Silt /%	-0.017	0.018	0.156	-0.241*	-0.082	-0.001	0.096
Clay /%	0.016	0.163	0.327***	0.575****	-0.001	-0.218	0.396****
SOC (%)	0.425****	0.214*	0.544****	0.531****	-0.008	0.303*	0.437****
DTPA- Fe	0.534****	0.170	0.776****	0.761****	0.007	0.517****	0.770****
DTPA- Mn	0.486****	0.009	0.568****	0.656****	-0.127	0.290*	0.677****
DTPA- Cu	0.166	-0.005	0.557****	0.746****	-0.086	0.216	0.604****
DTPA- Zn	0.020	0.046	0.683****	0.795****	-0.367**	0.201	0.716****
Level of significance at *P* = 0.05 (*), 0.01 (**), 0.005 (***) and 0.0005 (****)							

3.4. Effect of altitudinal gradients on micronutrient concentrations

All the four micronutrients responded differently and non-linearly to altitudinal gradients at an interval of 500 m increment till 4100 m masl across land uses (Fig. 5). They followed a non-linear, polynomial trend along the altitudinal gradients (< 500 m to 4100 m masl) (Fig. 5). The 6th – order (sextic) polynomial function fit best ($R^2 > 0.934$) for the relationships between micronutrients and altitudinal gradients. The Fe concentration (averaged of 500 m) increased consistently from base line elevation (0-500 m, 47.6 mg kg^{-1}) and reached the peak at 1000–1500 m masl (68.8 mg kg^{-1}) and then decreased inconsistently with several smaller peaks and valleys till 4000–4100 m masl (Fig. 5a). Contrary to Fe, Mn concentration decreased consistently from base line (15.6 mg kg^{-1}) till 1001–1500 m masl and then increased to reach the peak (26.5 mg kg^{-1}) at 1501–2000 m masl. Beyound 2000 m elevation, it decreased consistently and increased marginally at 4100 m masl (Fig. 5b). The Cu concentration increased inconsistently from base line (0.695 mg kg^{-1}) to reach first peak at 1501–2000 m (1.63 mg kg^{-1}) and then decreased inconsistently with smaller peaks and valleys 4000–4100 m masl (Fig. 5c). The Zn concentration, however decreased consistently from base line (1.02 mg kg^{-1}) till reached 1st peak at 1501–2000 m (1.751 mg kg^{-1}) and then increased inconsistently till reached the highest peak (2.92 mg kg^{-1}) at 4000–4100 m masl (Fig. 5d).

4. Discussion

The DTPA-extractable micronutrients in the acid soils (pH < 5.5) of north east India (NEI) varied widely across land uses and altitudinal gradients. This was expected due to highly variable nature of altitude mediated climate (tropical to alpine) with wide variability in mean annual rainfall (from 1200 to over 11300 mm) and temperatures (0.8 to 27.4° C). Wide variation in land uses practice (forest to upland and lowland agricultures to scrubs), with different degrees of degradations (deforestation to mining / jhum led erosion) was another possible reason for this variability. Variable physiography comprising Himalayan hills interspersed with valleys along steep altitudinal gradients (from < 15 m to > 4000 m masl) with heterogeneous soil properties including acidity (pH: 3.05–6.43), clay (< 10 to > 72%), and SOC contents (< 0.5 to > 5.0%) further caused variability in concentration of micronutrients in the region. Previous studies from the region (coal mine degraded Jaintia Hills, Meghalaya, Choudhury et al., 2017) reported a variation in average

DTPA-Fe concentration from 84 to 260 mg kg^{-1} while average DTPA-Mn varied from 7.2 to 13.5 mg kg^{-1}. Similarly, Shukla and Behera (2017) reported a wide variation in DTPA- Mn, Cu and Zn concentrations from traces up to 445, 136 and 52.9 mg kg^{-1}, respectively in different soil types of India. Our reported values of micronutrients (Table 3) in the acid soils of NEI fall within the reported ranges. Available micronutrients in the strong acidic soils (pH < 5.5) of hilly ecosystem of NEI developed from acid igneous rocks under alpine to tropical climate was in the order of: Fe > Mn > Zn > Cu. The order of micronutrient distributions depends on climate, vegetations, land use pattern, parent materials and soil properties including soil reactions (Sidhu and Sharma, 2010; Yitbarek et al., 2013; Yeshaneh, 2015). Our trends of Fe and Mn dominancy was, however, due to strong acidity (pH < 5.0 mostly) induced release of hydrous oxides of aluminum, Fe and Mn from the igneous parent materials (mostly sandstone origin) under tropical climate of the region (Patiram, 2007).

According to Sommers and Lindsay (1979), with each unit increase in soil pH from 4 to 9, the solubility of Fe in soil decreases by 1000-fold while it decreases 100-fold for Mn, Cu and Zn. We also observed a strong negative correlation of all four micronutrients with soil pH (r = -0.05 to -0.255). The soils from areas with higher clay in particular and SOC some extent also had significantly higher micronutrient concentrations. Correlation studies also affirmed a strong positive relation of micronutrients with clay (r = + 0.171 to + 0.507) and SOC (r = + 0.103 to + 0.230) contents. Step-wise multiple regression analysis also revealed that besides rainfall and elevation, three soil variables, namely clay, SOC and pH significantly ($p < 0.05$) influenced the availability of micronutrients (Table 5). Parameter estimation reflected steep and positive slopes of clay while negative of pH with all four micronutrients, suggesting that with an increase in clay content and decrease in pH, micronutrients increased significantly (Table 6). Soil pH strongly influences Zn availability and in acid soils, the influence is greater (Katyal and Randhawa, 1983). Similarly, SOC reflected positive slopes with Cu and Zn, suggesting that increase in SOC content significantly influenced Cu and Zn concentrations (Table 6). Positive influence of clay and SOC contents on micronutrient concentrations was also reported under different soil types in India (Sharma et al., 2006) and Southern Iran (Najafi-Ghiri et al., 2013).

Table 5
Pearson's correlation matrix between soil properties (particle size, pH, and SOC) and DTPA micronutrients (Fe, Mn, Cu and Zn/ mg kg− 1) in the soils (0–15 cm) depth across NE India.

Parameter	Sand	Silt	Clay	pH	SOC	Fe	Mn	Cu	Zn
Sand/%	1.000								
Silt/%	-0.561**	1.000							
Clay/%	-0.847**	0.108**	1.000						
pH	-0.127**	0.125**	-0.007	1.000					
SOC/%	-0.221**	0.156**	0.234**	-0.123**	1.000				
DTPA-Fe	-0.167**	0.115**	0.171**	-0.255**	0.119**	1.000			
DTPA-Mn	-0.267**	0.206**	0.204**	-0.171**	0.230**	0.106*	1.000		
DTPA-Cu	-0.244**	0.115**	0.242**	-0.049	0.103**	0.061	0.424**	1.000	
DTPA-Zn	-0.358**	-0.116**	0.506**	0.111**	0.222**	0.020	0.439**	0.455**	1.000

*Significant at $p < 0{\cdot}05$ level of significance (r = 0.0735); **Significant at $p < 0{\cdot}01$ level of significance (r = 0.103).

Table 6
Parameters of multiple regression of DTPA extractable micronutrient contents - Fe (Y1), Mn (Y2), Cu (Y3) and Zn (Y4) of elevation and soil variate of NE soils: clay, pH, SOC (Y1 = a0 + a1 × elevation + a2 × clay + a3 × pH + a4 x SOC); (Y2 = a0 + a2 × clay + a3 × pH + a4 × SOC); (Y3 and Y4 = a0 + a1 × elevation + a2 × clay + a3 × pH + a4 × SOC). The effect of climate variables (rainfall, temperature), other soil properties (bases, nitrogen, phosphorus, potash, sulfur, soil BD etc.) were marginal (non-significant at $P < 0.05$), so they were not included in the model. The residual degrees of freedom for Fe, Mn, Cu, and Zn are 551, 551, 557, and 555, respectively and the explanatory variables were significant at $P < 0.01$.

Parameter	DTPA-Fe	DTPA-Mn	DTPA-Cu	DTPA-Zn
	mg kg^{-1}			
F-ratio	$19.8_{(df-4,551)}$	$22.3_{(df-3,551)}$	$11.9_{(df-4,557)}$	$25.1_{(df-3,555)}$
a_0	-46.701	4.752	1.125	0.339
a_1	0.02	ns	0.03	0.0003
a_2	0.367	0.265	0.007	0.0091
a_3	-6.329	-0.122	-0.011	-0.023
a_4	0.07	0.12	0.067	0.005
R^2_{adj}	59.9	53.9	55.9	63.6
ns: non-significant at $p \leq 0.05$				

Land uses significantly ($p < 0.05$) influenced micronutrients in the studied soils; evident from the constructed diffograms among the seven landuses (Fig. 2). Scrub lands (SL) were earlier under forests in upland steep slopes of NEI. However, due to continuous large-scale deforestation in the form of open cast coal mining, jhumming and bun-agricultures (along the steep slope) and on repeated re-cultivation on post-jhum short fallow periods (2–3 years) transformed them into degraded land (Choudhury et al., 2016; 2017; NRSC, 2019). The abandoned jhum lands (after 2–3 years of SC) in steep slopes losses top fertile soil layers from runoff and soil erosion in this high intensity rainfall zone (> 3500 mm annually). In 2–3 years of abandoned jhum periods, they transform to barren, rocky degraded land (devoid of any vegetative covers) and become highly susceptible to erosion. Another reason is deforestation from large scale open cast coal mining in the scrub forests followed by seepage and influx of acid mine drainage (AMD). The sulfur (12%), mineral contaminants (biogenic pyrites, marcasite, trace metals etc.) and heavy metal rich AMDs (mostly iron rich pyrites, aluminum oxides) on oxidation acidified the soils further (pH: 3.05-4.0) and contributed large concentrations of Fe (Sahoo et al., 2013; Choudhury et al., 2017). Despite strong acidic soil reaction, lack of Mn, Cu and Zn-containing minerals (sphalerite) in the coal deposits, partially from abundances of pyrites and aluminum oxides (Choudhury et al., 2017) and loss of top fertile soils (occasionally exceeds 100 t ha^{-1} yr^{-1}) in degraded jhum lands (Dabral et al., 2008) might have resulted in poor Mn, Cu, Zn concentrations (Carmona et al., 2009) than forests and grass lands. We also recorded > 2-fold higher soluble aluminum (AL) (> 36 mg kg^{-1}) in SL over EF and GL (14–17 mg kg^{-1}). However, the reported values of Mn, Cu, and Zn from uplands under SL were comparable to AMD contaminated lowland paddy soils from the region (Choudhury et al., 2017).

Shifting cultivation (SC) in its traditional form was ecologically viable since the fallow cycles were long enough (> 20 years) for post-jhum restoration of soil health. However, in the recent past, decline in virgin forests while increase in

population pressure, shorter fallow cycles (2–3 years) are not allowing regeneration of vegetative covers and restoration of soil health. The SC areas in the present study were freshly burned jhum lands, cultivated only for one season (0–1 year). Despite burning of vegetations, soils in SC had significantly ($p < 0.05$) higher micronutrients (Fe, Mn, and Zn) than the soils from sloppy upland agriculture (SA). Generally, deterioration led by soil erosion and loss of top fertile soils in jhum starts from second to third years of continuous cultivation of multiple crops and continues beyond 2–3 years of post-jhum fallow periods. On re-cultivation after short fallow cycles (2–3 years), runoff (20–39% of total rainfall) and soil loss becomes more severe (19.16 to 155.5 t/ha annually) in the region (Dabral et al., 2008; Devi and Choudhury, 2013; Lungmuana et al., 2018). In our SC areas, soils with freshly burned forests/vegetative covers were exposed to only one season rainfall and soil erosion process might yet to reach at causing soil losses, unlike in degraded abandoned jhum lands in the region under SL. Previous studies from the region also opined similar view that soil health including nutrient contents under fresh to one-year old SC are relatively better than 2–3 years old or abandoned jhum areas (Venkatesh et al., 2003; Biswas et al., 2012). In sloppy SA, cultivation of agricultural crops (mostly nutrient exhaustive maize and turmeric) reduced the concentration of available micronutrients. Repeated soil disturbances (removal of weed biomass and tillage activities) and continuous nutrient mining with complete absence of micronutrient replenishments from external sources (Choudhury et al., 2016) might have contributed to the decline in micronutrients in the soils under SA.

The soils under lowland paddy (LP) although subjected to similar nutrient mining as that of SA, yet, could retain higher organic matter (SOC: 2.39%). Prevailing anaerobic condition in wet land rice cultivation in LP unlike dry-aerobic condition in sloppy SA, it further helped in increasing mobility of micronutrients particularly while building up organic matter accumulation from lower rate of oxidation process (Sahrawat, 2004). In addition, these lands were cultivated for single season paddy (3–4 months) while in the remaining 8–9 months, they remained wet and fallow. During fallow period, contribution of biomasses from luxuriant weed growth and decomposition of paddy straw and root biomasses further helped in SOC accumulation. Paddy soils had significantly ($p < 0.05$) higher clay contents (weighted average, > 35%). All these might have contributed to significant higher micronutrients in LP than upland agriculture (SA and SC).

Grassland (GL) followed by forests (EF) registered higher soil Zn concentration than cultivated (SA, SC, LP, PH) and degraded (SL) land uses. This agrees with the study conducted by Mengiste et al. (2015) in Gambella Region of Ethiopia, where DTPA extractable Zn was higher in high altitude grazing lands compared to cultivated lands. Grassland soils were finer in texture with significantly higher in clay contents (> 39%), which might have contributed higher build-up of Zn since clay content had strong positive correlation with Zn contents (r = + 0.506**) in the soil (Table 5). Higher values of zinc (20–34 mg kg^{-1}) in GL were mostly measured in yak grazing high altitude (> 3000–4100 m masl) alpine region of Sikkim Himalaya. Deposition of yak excreta rich in Zn (Zhang et al., 2018) at sub-zero to less than 1° C temperature along with the extensive fibrous root systems of the grasses might have deposited substantial amount of organic matter, evident from significantly higher SOC contents (> 2.20%). Like clay, SOC contents also reflected significant positive correlation (r = + 0.222**) (Table 5) with Zn contents in the soils of NEI. Forest soils had higher clay and SOC contents, next to GL while relatively more acidic (0.39 unit less) than GL. Deposition of litter-falls without soil disturbances might have favoured accumulation of comparable DTPA-Fe, with GL but higher in Mn, Cu and second highest Zn contents only next to GL. Higher SOC contents (> 2.20%) in the dense forests and grass lands of NEI were also reported by Choudhury et al. (2016).

Degraded forest-scrub (SL) was distinctly apart from other LULCs while PH was in the transition zone between EF to SL, relatively closer to SL. Comparable soil properties (clay, SOC, pH, soluble aluminum) including micronutrients in PH with degraded SL might be other reason. We also recorded higher concentration of soluble aluminum (32 mg kg^{-1}) in PH, comparable to SL while almost double to EF and GL (14–17 mg kg^{-1}). The transformation of PH from previously forests (canopy density > 60%) to cultivation of agricultural plantation (tea, rubber) including poorly managed orchards

(citrus peach, pine apple etc.) in sloppy uplands reduced canopy density substantially (< 40%) and made them susceptible to high rainfall induced erosion. In addition, excessive application of acidity producing nitrogenous fertilizers particularly in tea growing areas further acidified the soil and reduced the availability of micronutrient concentrations (except Fe).

Across the studied region, DTPA-extractable micronutrients exhibited non-linear responses (polynomial trends) with increase in elevation from < 15 m to 4100 m at an interval of 500 m masl. Due to variable responses of micronutrients to altitudinal gradients under each land use practices, the interaction effect of altitude and land uses was non-linear and followed a complex polynomial function with best fit at 6th order model. In the region, maximum degradation of primary forests to scrub land (SL) had been experienced in the altitudinal range of 950 to 1500 m masl. Large scale open-cast coal mining, shifting agriculture (short-fallow of 2–3 years and abandoning), and severe form of soil disturbances from cultivation in raised beds (buns) across steep slopes (bun agriculture) mostly responsible for transformation of forests to scrubs. Soil erosion led topsoil loss from such land use practices exceeds critical threshold limit (12.5 t/ ha /year) by several fold at this altitudinal range. In addition, AMDs from coal mining in selective areas (Meghalaya) under SL contaminated the soils with excessive amount of oxides and hydroxides of Fe, sulfur (S) and aluminum (Al) several fold higher than toxic limits. We measured DTPA-Fe concentration 2.5 times higher than toxic thresholds (100 mg kg^{-1}), 3.5 folds higher soluble Al (toxic thresholds of 10 mg kg^{-1}) and 10-fold higher available form of S (toxic thresholds of 20 mg kg^{-1}) (Patiram 2007, Choudhury et al., 2017) with extremely acidic soil reaction (pH < 3.5). This might be the reason for registering the highest Fe concentration but lesser amount of other three micronutrients (Mn, Cu, and Zn) at1001-1500 m masl. Weak correlation between DTPA-Fe and other three micronutrients (Table 5) also indicated dominance of Fe marginalized the presence of other micronutrients, mostly due to anthropogenic land disturbances. Other reasons for low concentrations of Mn, Cu and Zn in the altitudinal range of > 900–1500 m masl is due to the transformation of forests to settled agriculture (SA) in high rainfall (> 3000 m annual) sloppy uplands. Cultivation of erosion permitting crops (maize, zinger, turmeric, root crops etc.) across steep slopes after clearing of natural vegetations in SA made them vulnerable to fertile topsoil losses to erosion (Choudhury et al., 2016). The predominant rainfed marginal input intensive practices in SA in the region completely lack in periodic nutrient replenishments from external sources (organic/inorganic) to balance soil micronutrient reserves from losses (erosion and runoff loss, nutrient leaching, continuous crop nutrient mining etc.). As a result, micronutrient concentrations in SA did not respond to altitudinal gradients (< 300 m to > 1800 m masl) (Figs. 3 and 4), rather was comparable to scrub land. Conversion of forests to freshly shifting agriculture (SC) and plantation crops (PH) in sloppy uplands, despite limited soil disturbances, we observed an increasing trend of four micronutrient concentrations, though significant ($p < 0.05 - 0.005$) only in Fe and Mn along the altitudinal gradient. This might be due to significant increase in SOC contents ($p < 0.05 - 0.005$) and more acidification (pH decreased by 0.25–0.33 units) of soils at higher altitudes (> 930 m masl).

However, dominance of non-disturbed primary forests (EF) and grass land (GL) beyound 1500 m masl resulted in higher concentrations of Mn, Cu (at 1501–2000 m masl) and Zn (GL at 4100–4200 m masl) (Fig. 5b-d). Micronutrient concentrations in EF and GL increased significantly ($p < 0.005$) along the altitudinal gradient. Among the cultivated land uses, lowland paddy (LP) was an exception where the positive and significant ($p < 0.005$) increasing trend of micronutrients, SOC and clay contents along the altitudinal gradient (20-2000 m) was comparable with EF and GL (Figs. 3–4, Table 4). Presence of LP at 1501–2000 m also contributed in higher Mn and Cu concentrations at 1501–2000 m masl. Presence of GL at high-altitude (> 3000 m masl) alpine region of Sikkim Himalaya resulted in higher concentration of Zn at 4000–4200 m masl.

Correlation studies of soil properties with elevation under each land use affirmed that positive influence of altitude mediated changes in soil properties (higher SOC, clay) on micronutrient concentrations confined only in non-disturbed

(EF and GL) and relatively stable cultivated lowlands (LP) (Table 4). In cultivated sloppy uplands, range of unsustainable cultivation practices at different intensities of disturbances (deforestation, burning of vegetations, soil pulverization, and growing of nutrient exhaustive multiple crops) and scrub lands offset the positive influence of altitude mediated changes on soil properties including micronutrient concentrations. Altitudinal variation modifies temperature, in turn controls decomposition of organic matter and accumulation of SOC (Choudhury et al., 2016). We observed consistent increase in SOC and clay contents only in non-disturbed land uses (EF, GL) along with LP as an exception compared to inconsistent trends in disturbed land uses. As a result, the measured SOC and clay contents in our study followed a non-linear polynomial 5th order function across altitudinal gradient (< 500 m till 4200 m masl) and so, thus micronutrient concentrations. Differences in SOC content and PSD particularly clay contents associated with changes in physiography strongly influences micronutrient distributions in soil (Sharma et al., 1992).

Conclusion

We conclude that plant available micronutrients Fe, Mn, Cu and Zn extracted by DTPA in the acid soils of the hilly ecosystem of North east India (Eastern Himalaya) exceeded by far critical limits for Indian soils namely 8.5 mg kg^{-1} soil for Fe, 7.0 mg kg^{-1} soil for Mn, 0.8 mg kg^{-1} soil for Cu, and 1.2 mg kg^{-1} soil for Zn. Mean Fe, Mn, Cu and Zn concentrations were 58.76, 20.37, 1.09, and 1.78 mg kg^{-1}, respectively. Soils under primary forest (EF) recorded mean Fe, Mn, Cu, and Zn concentrations of 48.7, 30.5, 1.74 and 2.13 mg kg^{-1}, respectively. Conversion of forests to upland agriculture (shifting and settled) significantly ($p < 0.05$) reduced concentrations of Fe (-17.7 to -28.1%), Mn (− 41.5 to -78.8%), Cu (-53.4 to − 60.9) and Zn (-33 to -41%) while cultivation in lowland (LP), the reduction in Mn (-21.8%), Cu (−40.8%) and Zn (-23.5%) was relatively less. Cultivation of plantation crops (PH) in sloppy uplands also substantially reduced Mn (-41.5%), Cu (60.9%) and Zn (-50.2%) than EF. Large scale open-cast coal mining led acidification followed by metal contamination (Fe rich pyrites) and erosion of topsoil from repeated short fallow shifting cultivation, bun agriculture etc. along steep slopes degraded the forests to scrub land (SL). As a result, concentration of micronutrients (except Fe) further decreased (-66.1 to -80.6%) in SL while Fe concentration increased (+ 73%) over EF. However, non-cultivated grass lands (GL) at high altitude had comparable Fe, Mn and Cu but higher (+ 29%) in Zn concentrations than EF.

Micronutrients responded differently and followed a non-linear, 6th − order polynomial trend along the altitudinal gradients (< 500 m to 4100 m masl). This was mostly attributed to dominance of specific type of land use (s) at particular altitudinal ranges. Altitudinal ranges with maximum concentrations also influenced by the type of land uses practiced. This was also evident from the visible altitude mediated positive influence on soil properties including micronutrient concentrations only in non-cultivated land uses (EF and GL) with an exception to cultivated lowlands. Overall, wide variability in plant available micronutrients could well be explained as an outcome of the interaction from land uses and altitudinal gradient mediated changes in key soil properties namely pH, clay and organic carbon contents, which together contributed 54−64% variation in the soils of the region.

Declarations

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Author contributions (names must be given as initials)

B.U.C collected the sample did the data analysis, prepared all figures and wrote the main manuscript. M.A.A did micronutrient analysis, M.C. and T. T. Meetei analyzed the soil sample for different soil properties.

Competing interest

The authors declare no competing interests.

Additional information

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Figures

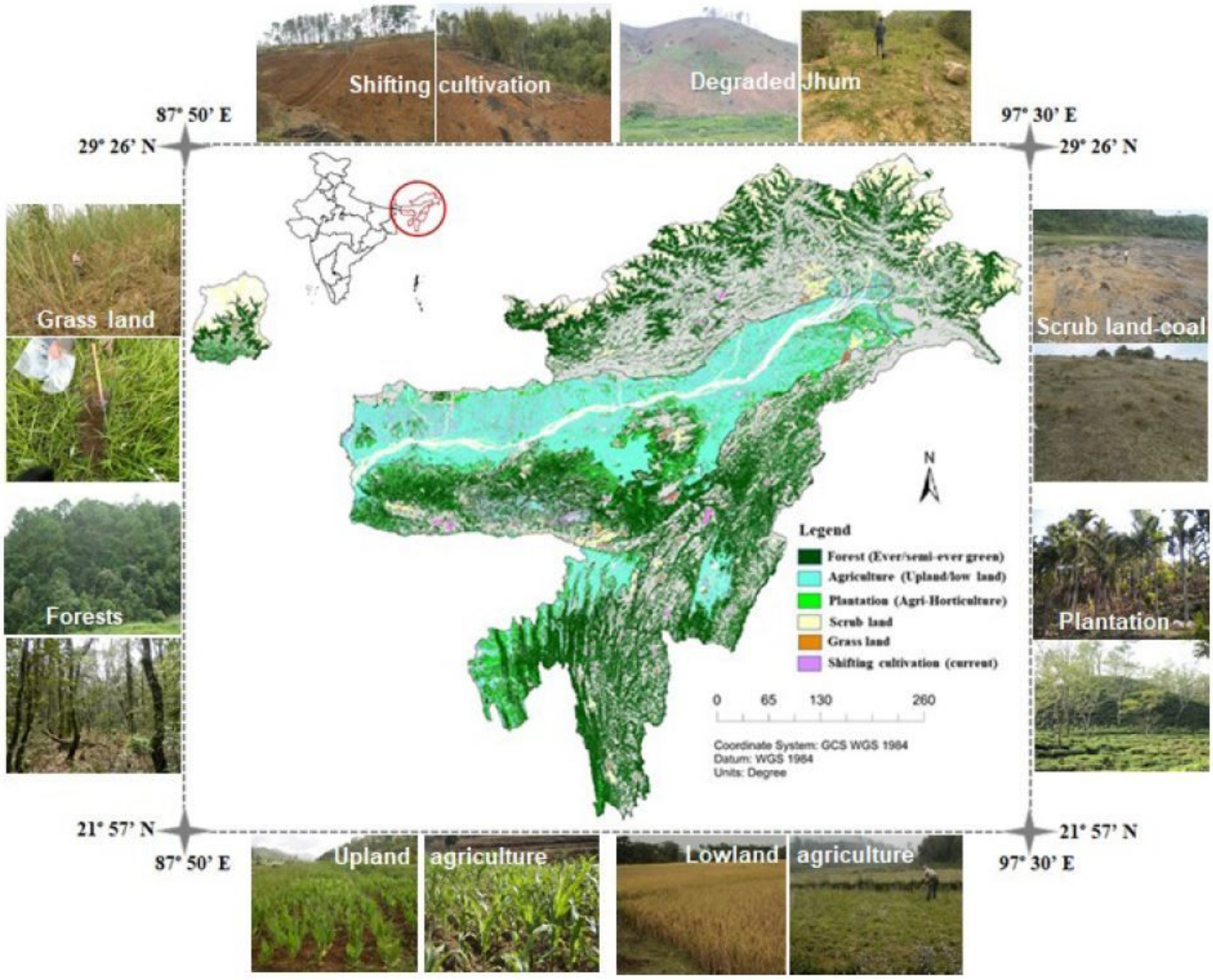

Figure 1

Landuse map of the study area (North-eastern Region of India) derived from multi-date Resourcesat-2 ortho-rectified LISS-III satellite data of 2015-16. Source: Modified and adopted from NRSC (2019). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

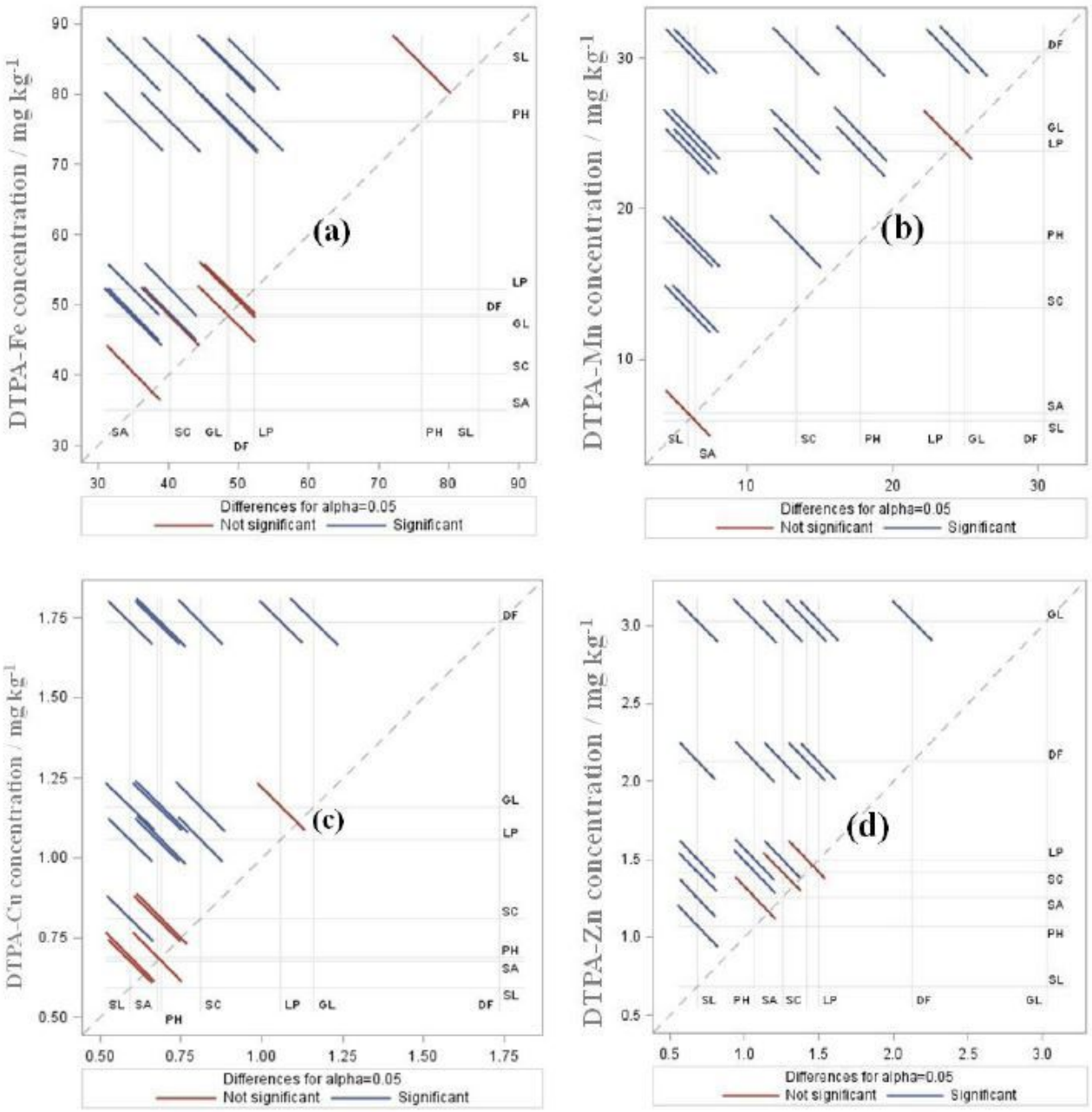

Figure 2

Diffograms showing significant differences among the seven land uses in available Fe, Mn, Cu and Zn contents. Bold horizontal and vertical lines represent the seven land uses of North-east India. The small lines passing through the squares diagonally represent non-significant or significant differences between the two corresponding land uses. Treatment abbreviations are explained in text.

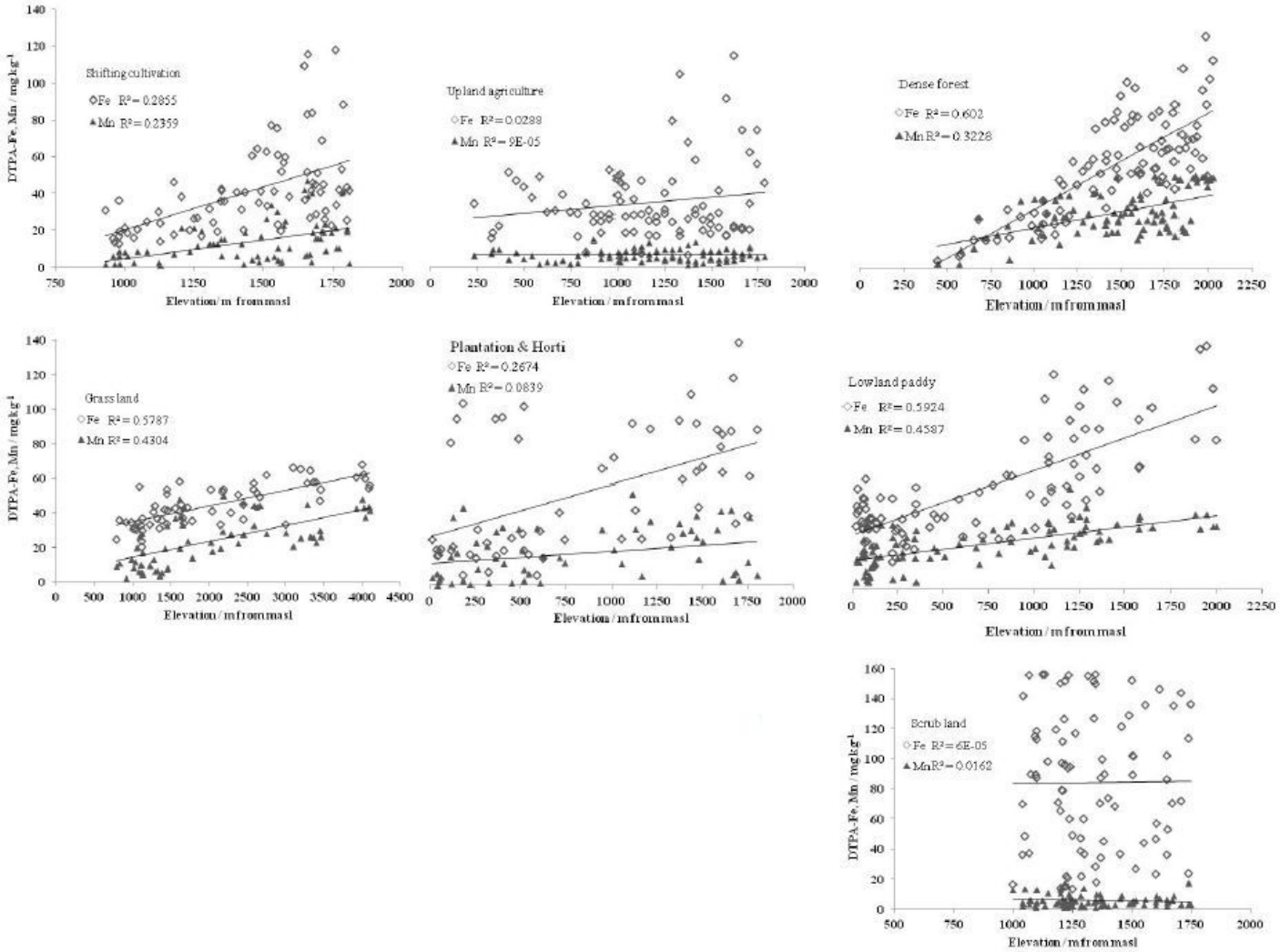

Figure 3

Effect of land uses on response of DTPA extractable Fe and Mn (mg kg-1) concentrations along the altitudinal gradients.

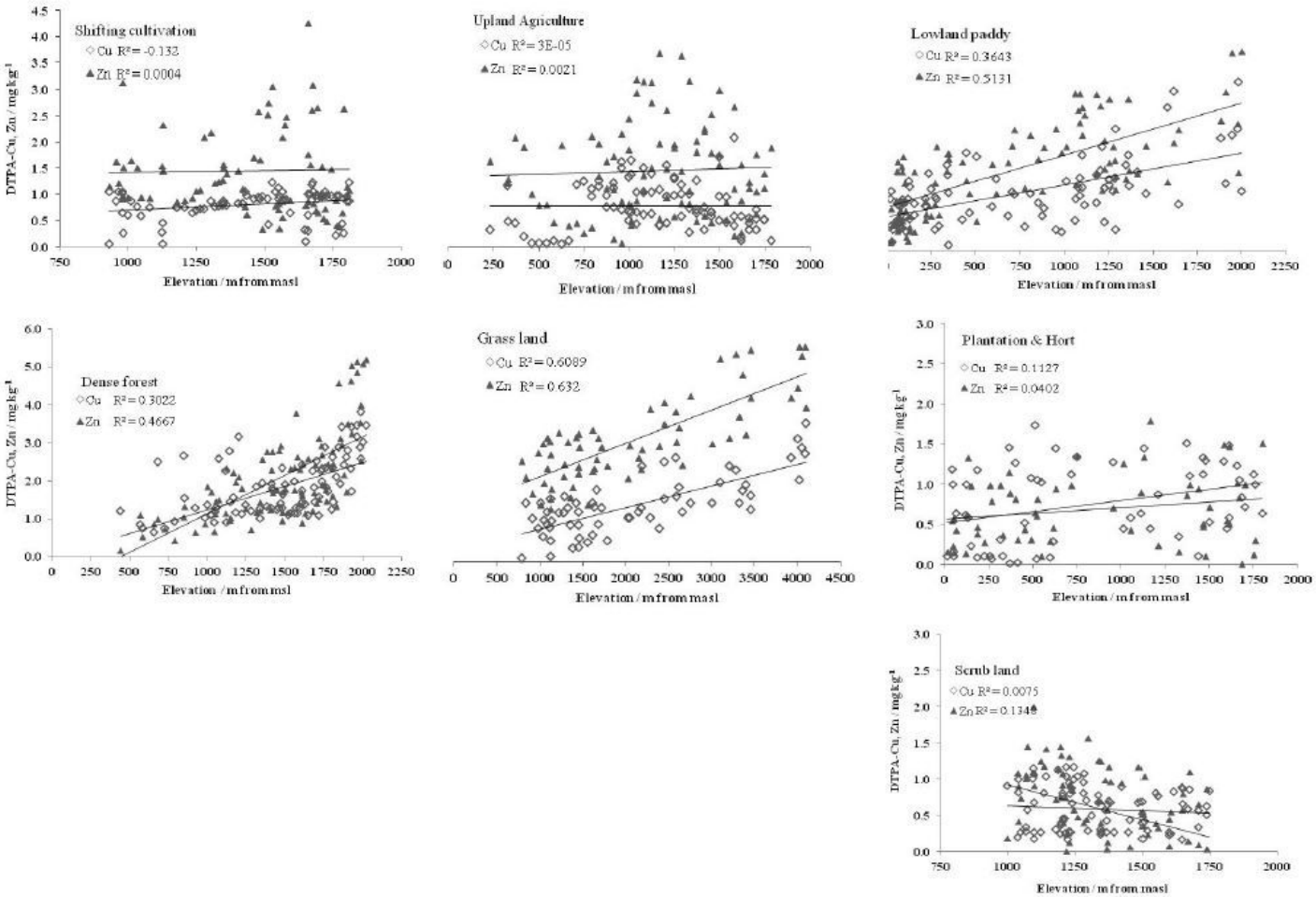

Figure 4

Effect of land uses on response of DTPA extractable Cu and Zn (mg kg-1) concentrations along the altitudinal gradients.

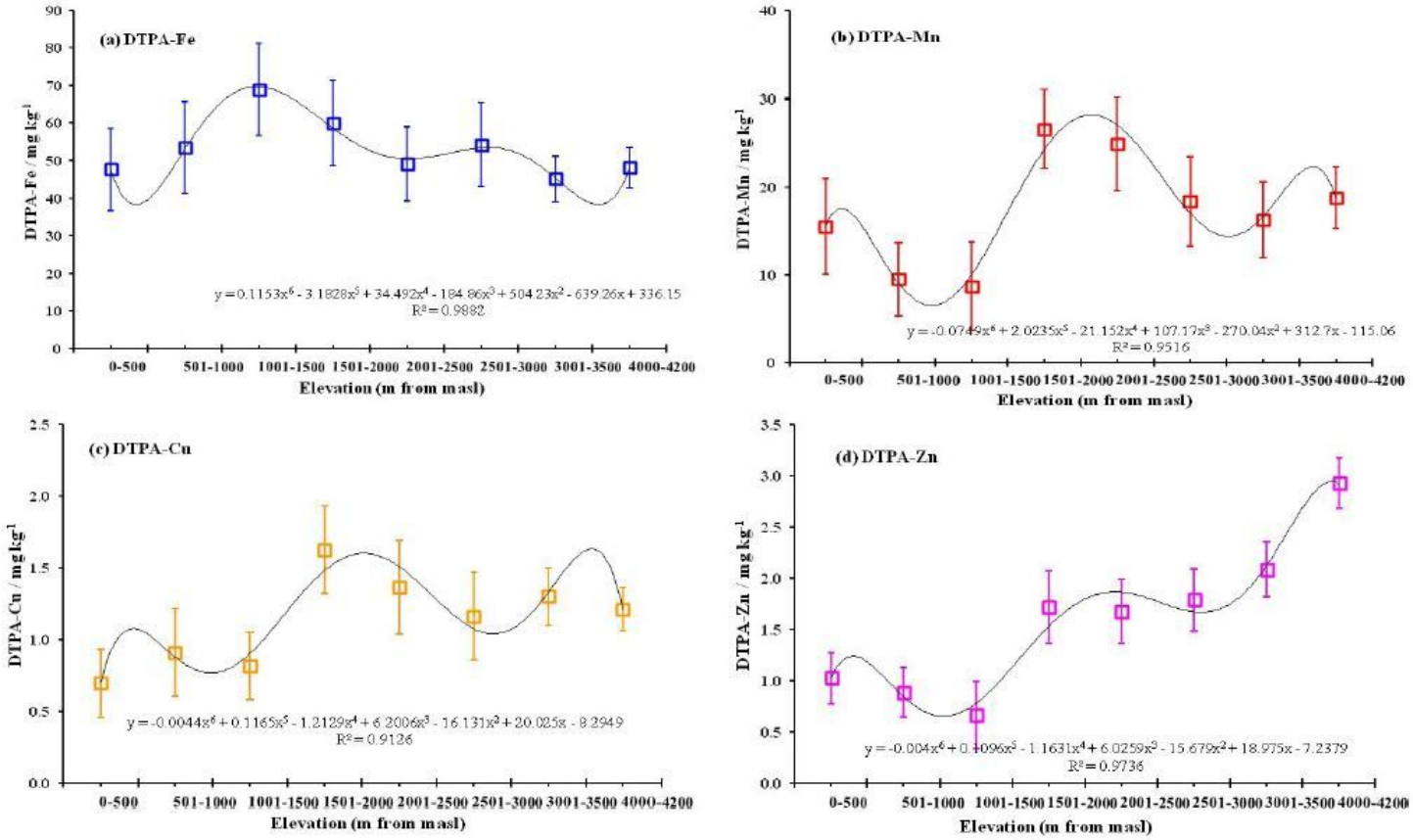

Figure 5

Altitudinal gradients (<15 m to >4000 m masl) on DTPA-extractable (a) Fe (b) Mn (c) Cu and (d) Zn concentrations. Dotted lines are polynomial trends.