Agric Res
https://doi.org/10.1007/s40003-018-0327-5

FULL-LENGTH RESEARCH ARTICLE

Priority Zoning of Available Micronutrients in the Soils of Agro-ecological Sub-regions of North-East India Using Geo-spatial Techniques

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Received: 1 March 2017 / Accepted: 5 March 2018

Abstract An attempt was made to identify priority zones of available micronutrients in the soils of agro-ecological sub-regions (AESR) of north-eastern states of India (Assam, Nagaland, Sikkim and Tripura) using geo-spatial techniques. Surface soil samples (0–25 cm) were collected from Assam (AESRs 15.2, 15.3, 15.4 and 17.1), Nagaland (AESR 17.1), Sikkim (AESR 16.2) and Tripura (AESR 17.2) and analysed for pH, organic carbon and DTPA-extractable micronutrients (Fe, Mn, Zn and Cu) by standard procedures. Regular Spline was employed as spatial interpolation techniques for obtaining spatial distribution of available micronutrients in soils. The AESR map was overlaid on spatial distribution layers to obtain spatial variability of micronutrients in the AESRs of north-eastern regions of India. Zinc deficiency was common in all the AESR. Maximum deficient area of Zn, Mn and Cu was observed in AESR 15.4, and it was regarded as the high-priority zone, whereas AESR 16.2 and AESR 17.2 were considered as low-priority zone. Rainfall, pH and organic carbon appeared to be the key factors in controlling micronutrient availability in soils of north-eastern regions of India.

Keywords Agro-ecological sub-regions · Micronutrient · Priority zone · Spatial interpolation · Assam · Nagaland · Sikkim · Tripura · Iron · Copper · Manganese · Zinc

Introduction

The importance of micronutrients in maintaining soil fertility status [18] as well as food and nutritional security in India [38] is well known. Micronutrient deficiencies in crops are widespread all over the world because of their increasing demands from intensive cropping practices [10]. In India, intensive cropping with high-yielding crop varieties for enhancing food grain production has catalysed rapid depletion of available micronutrients in surface soil [40]. Advanced techniques including global positioning system (GPS) and geographic information system (GIS) facilitate soil micronutrient mapping and provide quantitative support for decision and policy making to improve agricultural productivity with balanced micronutrient nutrition [48]. The extent and distribution of micronutrients is best comprehended by assessment of their spatial variability [30], i.e. occurrence with reference to earth surface [22]. Spatial variability of micronutrient across the agro-ecological zones [43] may provide comprehensive understanding of their nature and distribution which was influenced by climate, physiography, soil types and vegetation [37]. The north-eastern regions of India has versatility in climate, physiography and soils, and hence micronutrient availability is also highly variable [7, 8, 14]. However, systematic and region specific information on spatial distributions of available micronutrients on a large scale is either scanty or sporadic [49]. One of the recent

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advancements of region-based soil-micronutrient mapping is the priority zoning [39]. Priority zoning is one of the recent approaches to represent spatial variability of one or more objects in GIS by multi-criteria evaluation [11]. Multi-layer priority zoning may help in developing multi-nutrient decision support for efficient micronutrient use in soils. Agro-ecological region-based priority zone mapping of micronutrients would be a very efficient measure for micronutrient management in soils of north-eastern regions of India [15, 32]. Thus, the present study is aimed at spatial distribution of DTPA-extractable micronutrients in soils under various agro-ecological situations of north-eastern regions of India by adopting priority zoning technique in GIS environment.

Materials and Methods

Study Area

The states of Assam (including 16 National Food Security Mission Districts), Nagaland, Sikkim and Tripura were identified for soil sampling covering a total survey area of 7,709,000 ha within the geographic extent of 88°E–98°E longitude and 22°N–29°N latitude. The study area includes 4 agro-ecological sub-regions of India (Figs. 1, 2).

Sampling Procedure

Pre-field base maps were prepared using representative Survey of India Topographical sheets) at 1:50,000 scale by geo-registration using polyconic projection and WGS 84 datum in GIS platform. The grid points were demarcated at 0.5 km interval for cultivated lands of Sikkim, 1.0 km interval for Assam and Nagaland and 2.0 km interval for Tripura. The administrative boundaries in the Survey of India topographical sheets were carefully demarcated in the geo-referenced base maps for each state. The state-level base maps were further segregated by delineation of boundaries at district level. Finally, district-level base maps were used for carrying out the survey work. Soil survey has been conducted in all the four districts of Tripura (West Tripura, South Tripura, Dhalai and North Tripura), 16 National Food Security Mission (NFSM) districts of Assam (including Kokrajhar, Barpeta, Baksa, Goalpara, Bangaigaon, Chirang, Nalbari, Karbi-Anglong, Marigaon, Nagaon, Sonitpur, Darrang, Udalguri, Lakhimpur, Dhemaji and Tinsukia), all the 11 districts of Nagaland (Dimapur, Kohima, Peren, Wokha, Mokokchung, Mon, Zunheboto, Phek, Kiphire, Longleng and Tuensang) and all the four districts of Sikkim (North, East, West and South Sikkim) during 2008–2012, by collecting geo-referenced surface soil samples (0–25 cm) at 2.0, 1.0 and 0.5 km intervals, respectively, covering 6 agro-ecological sub-regions (15.2, 15.3, 15.4, 16.2, 17.1 and 17.2) of north-eastern states (Table 1). In Sikkim, since most of the terrains are not easy

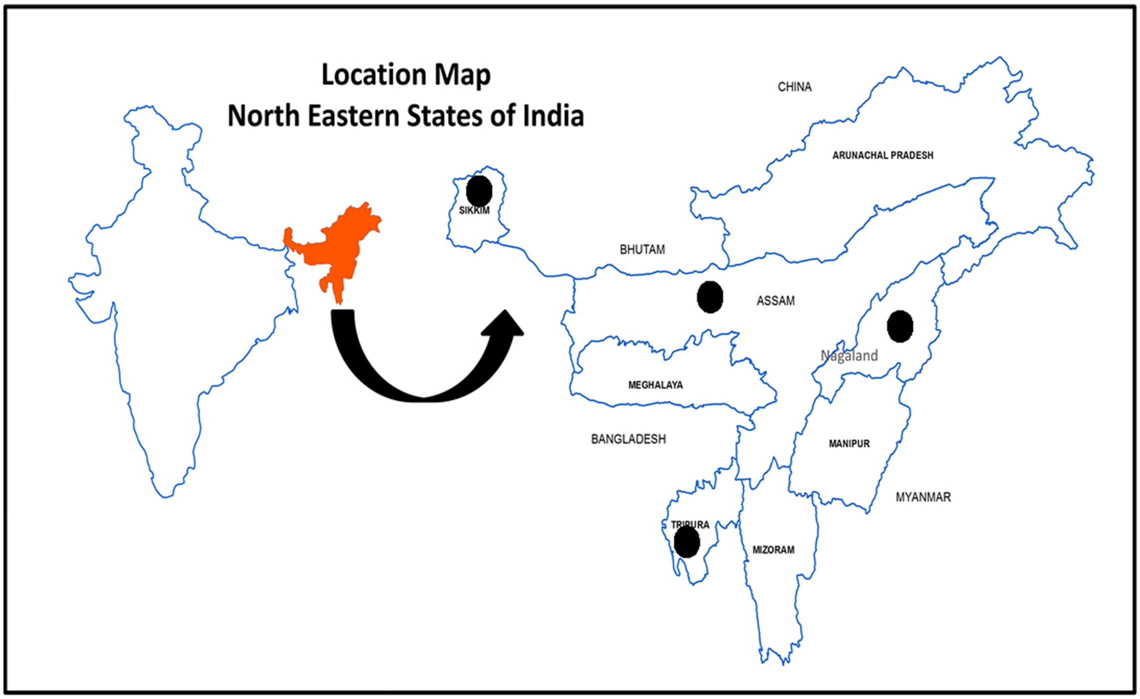


Fig. 1 Location map of the study area

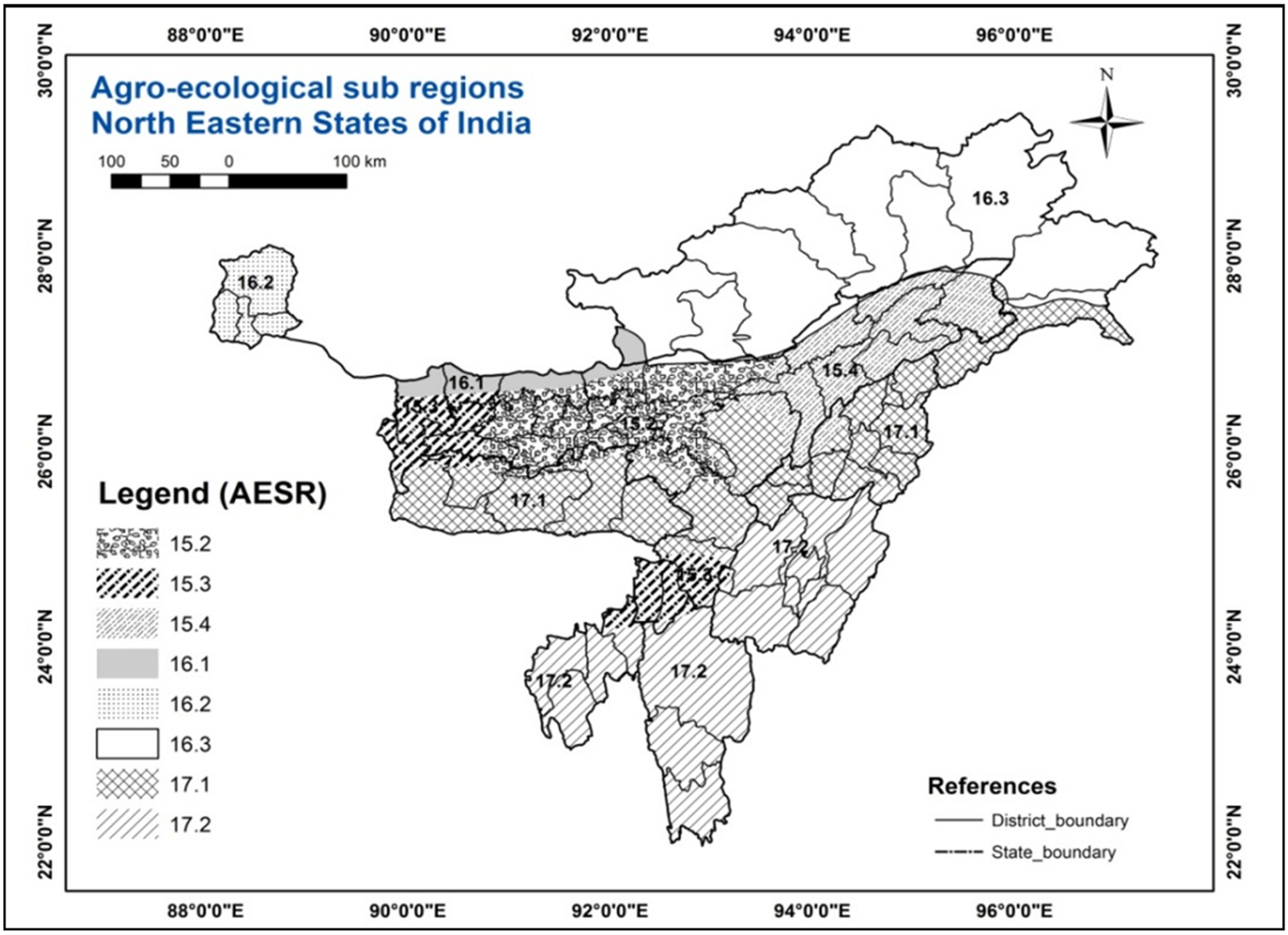


Fig. 2 Agro-ecological sub-regions of NE regions of India

to access due to very steep hill slopes with rocky and snow caped mountainous topography, soils were collected from arable lands only. Totally, 36,500 soil samples were collected comprising 20,031 samples in Assam, 8484 in Nagaland, 5560 in Sikkim and 2425 in Tripura. Because of the insufficient number of sampling and inaccessibility and remoteness of locations, AESR 16.1 (minor parts of Assam bordering to Bhutan) and AESR 16.3 (Arunachal Pradesh) were not considered for the present investigation.

Soil Analysis

The soil samples were analysed for pH (1:2.5 H_2O) [23], organic carbon [45] and available Fe, Mn, Zn and Cu with 0.005 M DTPA extractant [25] using atomic absorption spectrophotometer. Soils are grouped into different classes for fertility assessment as per the standard guidelines. Soil reaction (pH) is grouped as extremely acidic (< 4.5), very acidic (4.5–5.0), strongly acidic (5.0–5.5), moderately acidic (5.5–6.0), slightly acidic (6.0–6.5) and neutral (6.5–7.0). Soils have been rated as low (< 0.40%), medium (0.40–0.75%) and high (> 0.75%) for organic carbon [42]. The analytical data for micronutrients were categorized as deficient and sufficient level, considering the critical limit of each element. The concentration of micronutrients above critical limit has been considered as sufficient and that below the critical limit as deficient. In this rationale, deficiency and sufficiency of available Fe (< 4.5 mg kg^{-1} >) [25], available Mn (< 3.5 mg kg^{-1} >) [6, 29], available zinc (< 0.6 mg kg^{-1} >) [25] and available Cu (< 0.2 mg kg^{-1} >) were considered [25]. Average rainfall data available for 30 years (1980–2010) from district-wise rainfall stations of Assam, Nagaland, Tripura and Sikkim states were collected to understand the relationship between rainfall and soil parameters [26, 41]. All the data bases rainfall and soil were fed into SPSS ver. 15.0 for Pearson's bi-variate statistics.

Data Interpretation in GIS

State- and district-wise soil databases were designed in MS Excel and further fed and processed in GIS platform using

Table 1 Soil sampling procedure in various agro-ecosystems of NE regions of India

AESR	Descriptions	State	Districts-wise soil sampling	Sampling procedure
15.2	Middle Brahmaputra plains, hot, humid agro-ecological sub-region	Assam	Barpeta (1090), Baksa (965), Nalbari (435), Sonitpur (2145), Darang (605), Udalguri (808), Nagaon (2055) and Morigaon (790)	1.0-km grid intervals (except inaccessible forests and river bed areas)
15.3	Lower Brahmaputra plains and Barak valleys, hot, moist, humid to per-humid ecological sub-region	Assam	Bangaigaon (795), Chirang (970), Goalpara (800) and Kokrajhar (1580)	1.0-km grid intervals (except inaccessible forests and river bed areas)
15.4	Upper Brahmaputra plains, warm to hot, per-humid ecological sub-region	Assam	Tinsukia (1750), Lakhimpur (1120), Dhemaji (1515)	1.0-km grid intervals (except inaccessible forests and river bed areas)
16.2	Eastern (Sikkim) Himalayas, warm, per-humid ecological sub-region	Sikkim	East Sikkim (1703), West Sikkim (1638), South (1731) and North Sikkim (488)	0.5-km grid intervals of arable lands
17.1	Karbi-Anglong Proper (Mikir hill ranges) and Purvanchal hills, warm to hot, humid to per-humid ecological sub-region	Assam	Karbi-Anglong (2608)	1.0-km intervals (except inaccessible forests and river bed areas)
	Purvanchal hills, warm to hot, humid to per-humid ecological sub-region	Nagaland	Dimapur (469), Kohima (705), Peren (910), Wokha (806), Mokokchung (798), Zunheboto (718), Longleng, Mon, Tuensang (998), Kiphire (665) and Phek (1029)	1.0-km intervals (except inaccessible rocky mountainous areas)
17.2	Purvanchal hills (Tripura-Mizoram geo-synclinal formation), warm to hot, per-humid ecological sub-region	Tripura	West Tripura (700), South Tripura (525), Dhalai (495) and North Tripura (705)	2.0-km intervals in all accessible areas (except inaccessible forests)

Arc-GIS software (version 10.0). Once the databases were incorporated in attribute table, Spatial Interpolation method was employed to generate spatial distribution of soil parameters including pH, organic carbon and micronutrients (iron, manganese, zinc and copper) by *Regular Spline* technique [16, 21]. The algorithm used for the Spline tool uses the following formula for the surface interpolation:

$$S(x,y) = T(x,y) + \sum_{J=1}^{N} \lambda_j R(rj)$$

where $j = 1, 2, \ldots, N$. N is the number of points. λ_j are coefficients found by the solution of a system of linear equations. rj is the distance from the point (x, y) to the jth point. $T(x, y)$ and $R(r)$ are defined differently, depending on the selected option.

Raster reclassification technique was exercised to impart range values of soil parameters (pH, O.C. and micronutrients) as stated in soil analysis component. After categorizing the soil parameters into various ranges, spatial variability under each category has been evaluated. Agro-ecological sub-region map layer was superimposed on spatial distribution of soil parameters. Using *Raster Clipping* technique, spatial variability of individual soil parameters under various agro-ecological sub-regions of North East India was ascertained from GIS-based attribute table. State- (Tables 2, 3) and AESR-wise database (Tables 4, 5) on spatial distribution of soil parameters were collated in GIS platform.

Priority Zoning

Priority zoning method has been applied in many fields including agricultural land use planning [24], morphometric analysis of watershed [5, 33, 34], geo-sciences and natural resource mapping [46]. However, in the present study, first time attempt has been made on priority zoning of micronutrients under different AESR of north-eastern region of the country (Fig. 3). Priority zoning was made categorizing low-, medium- and high-priority zones of micronutrients building decision trees in GIS platform. The hypothesis was made such that high-priority zone should have more proximity of deficient status of micronutrients in terms of percentage of area distribution and vice versa. For each micronutrient, percentage of total surveyed area (TSA) under deficient status was given ranking based on a scale of 1–10. Lowest rank was imposed to highest percentage of TSA value and vice versa. Composite weightage was given by to obtain priority zone rating in three distinct categories, viz, low, medium and high. Low-priority zone has weightage of less than 25 value, medium as 25–35 and

Table 2 State-wise spatial distribution of soil parameters of NE regions

State	Total surveyed area (TSA) (000′ ha)	Spatial distribution of soil parameters in 000′ ha (% of TSA)					
		pH (1: 2.5 H_2O)			O.C. (%)		
		< 5.5	> 5.5	> 7.0	Low	Medium	High
Assam	4870	3525 (72.4)	1007 (20.7)	145 (3.0)	548 (11.3)	652 (13.4)	3333 (68.4)
Nagaland	1658	1386 (83.6)	272 (16.4)	0 (0.0)	20 (1.2)	41 (2.5)	1597 (96.3)
Sikkim	129	68 (53.0)	61 (47.0)	1 (0.9)	7 (5.3)	14 (10.5)	109 (84.2)
Tripura	1052	868 (82.5)	100 (9.5)	0 (0.0)	120 (11.7)	743 (70.6)	106 (10.1)
Total	7709	5848 (75.9)	1440 (18.7)	146 (1.9)	695 (9.0)	1449 (18.8)	5144 (66.7)

Table 3 State-wise spatial distribution of available micronutrients in soils of NE regions

State	TSA (000′ ha)	Spatial distribution of soil micronutrients in 000′ ha (% of TSA)							
		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})		Cu (mg kg^{-1})	
		Deficient	Sufficient	Deficient	Sufficient	Deficient	Sufficient	Deficient	Sufficient
Assam	4870	286 (5.9)	4247 (87.2)	508 (10.4)	4024 (82.6)	1625 (33.4)	2909 (59.7)	315 (6.5)	4218 (86.6)
Nagaland	1658	7 (0.4)	1651 (99.6)	65 (3.9)	1593 (96.1)	238 (14.4)	1420 (85.6)	44 (2.7)	1614 (97.3)
Sikkim	129	0 (0.0)	129 (100.0)	10 (7.9)	119 (92.1)	20 (15.7)	109 (84.3)	6 (5.0)	123 (95.0)
Tripura	1052	0 (0.0)	969 (92.1)	0 (0.0)	969 (92.1)	172 (16.4)	785 (74.6)	0 (0.0)	969 (92.1)
Total	7709	292 (3.8)	6996 (90.8)	584 (7.6)	6705 (87.0)	2055 (26.7)	5221 (67.7)	365 (4.7)	6923 (89.8)

Table 4 AESR-wise spatial distribution of soil parameters s of NE regions

AESR	Total surveyed area (TSA) (000′ ha)	Spatial distribution of soil parameters in 000′ ha (% of TSA)					
		pH (1: 2.5 H_2O)			O.C. (%)		
		< 5.5	> 5.5	> 7.0	Low	Medium	High
15.2	2020	1361 (67.4)	420 (20.1)	49 (2.4)	141 (7.0)	285 (14.1)	1356 (67.1)
15.3	869	559 (64.4)	271(31.2)	88 (10.1)	80 (11.2)	108 (12.5)	642 (73.9)
15.4	938	745 (79.5)	132 (14.1)	8 (0.8)	111 (9.8)	100 (10.7)	666 (71.0)
16.2	129	68 (53.0)	61 (47.0)	1 (0.9)	7 (5.3)	14 (10.5)	109 (84.2)
17.1	2701	2246 (83.2)	456 (16.9)	0 (0.0)	236 (8.7)	200 (7.4)	2266 (83.9)
17.2	1052	868 (82.5)	100 (9.5)	0 (0.0)	120 (11.7)	743 (70.6)	106 (10.1)
Total	7709	5848 (75.9)	1440 (18.7)	146 (1.9)	695 (9.0)	1449 (18.8)	5144 (66.7)

high as more than 35 value). The exercise was followed for all the micronutrients in all the 6 AESRs (Tables 7, 8).

Results

Soil pH

State- and District-wise Spatial Distribution of Soil pH

In Assam, maximum TSA under pH < 5.5 belonged to Lakhimpur district (93.6%) followed by Sonitpur (91.9%), Darrang (89.9%) and Udalguri district (86.3%). In Nagaland, maximum area under pH < 5.5 belonged to Mokokchung (98.3%) and Wokha district (98.3%). In Sikkim, soil under pH less than 5.5 was maximum in East Sikkim (73.0%), whereas in Tripura, it was maximum in South Tripura district (97.5%) (Fig. 4). These districts need much attention for systematic liming for overcoming soil acidity problems.

AESR-wise Spatial Distribution of Soil pH

It was noted that 75.9% of total surveyed area (TSA) covering all the AESRs of NE states was under acid soils having pH less than 5.5. These soils were chemically

Table 5 AESR-wise spatial distribution of available micronutrients in soils of NE Regions

AESR	TSA (000′ ha)	Spatial distribution of soil micronutrients in 000′ ha (% of TSA)							
		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})		Cu (mg kg^{-1})	
		Deficient	Sufficient	Deficient	Sufficient	Deficient	Sufficient	Deficient	Sufficient
15.2	2020	69 (3.4)	1712 (84.8)	135 (6.7)	1646 (81.5)	616 (30.5)	1166 (57.7)	46 (2.3)	1736 (85.9)
15.3	869	24 (2.7)	807 (92.9)	79 (9.1)	752 (86.5)	361 (41.6)	470 (54.0)	9 (1.1)	821 (94.5)
15.4	938	36 (3.9)	841 (89.7)	94 (10.1)	783 (83.5)	416 (44.4)	461 (49.2)	86 (9.1)	792 (84.4)
16.2	129	0 (0.0)	129 (100.0)	10 (7.9)	119 (92.1)	20 (15.7)	109 (84.3)	6 (5.0)	123 (95.0)
17.1	2701	164 (6.1)	2538 (93.9)	265 (9.8)	2436 (90.2)	470 (17.4)	2232 (82.6)	218 (8.1)	2483 (91.9)
17.2	1052	0 (0.0)	969 (92.1)	0 (0.0)	969 (92.1)	172 (16.4)	785 (74.6)	0 (0.0)	969 (92.1)
Total	7709	292 (3.8)	6996 (90.8)	584 (7.6)	6705 (87.0)	2055 (26.7)	5221 (67.7)	365 (4.7)	6923 (89.8)

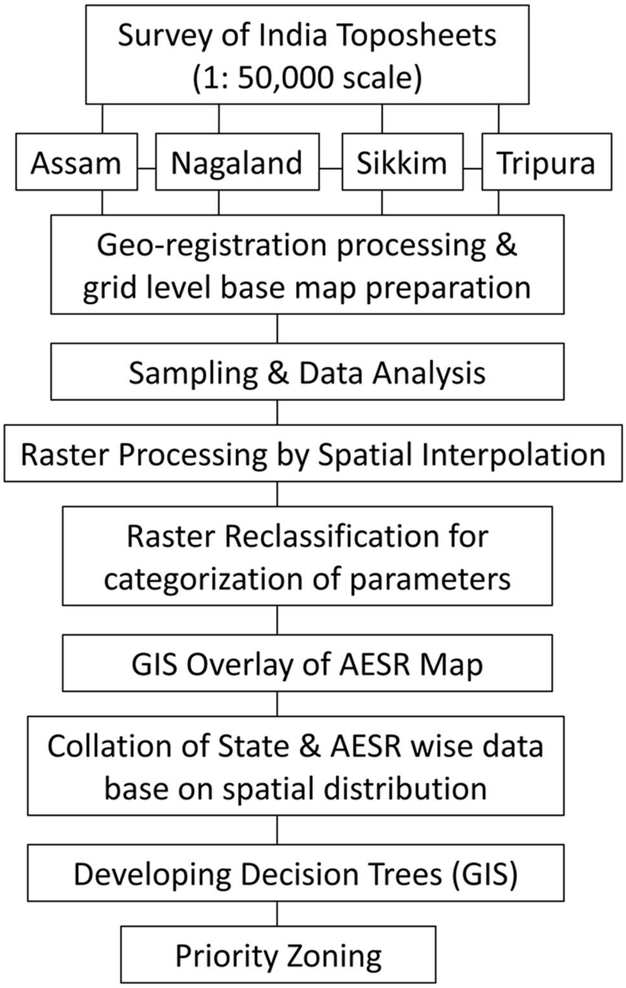


Fig. 3 Methodology of priority zoning

degraded with declined top soil fertility status, in which, maximum affected area was under AESR 17.1 (83.2% of TSA) due to unscientific cultivation like *jhumming* and soil erosion [31, 36]. Strong soil acidity is attributed to the formation of soils from alumino-silicate-rich acidic parent materials (ferruginous sandstones and shales) under humid subtropical climate [1, 4, 19]. Neutral to slightly alkaline soils (pH > 7.0) occupied only 1.9% of TSA in all the AESRs and predominant in AESR 15.3 (10.1% of TSA). These soils are mostly formed in marshes and swamps [12] along the river bank of Brahmaputra with elevated pH due to prolonged water logging and low permeability [13].

Organic Carbon (O.C.)

State- and District-wise Spatial Distribution of O.C.

Low organic carbon content was mostly found in the soils of Tinsukia (23.9% of TSA), Karbi-Anglong (20.7%), Baksa (19.7%) and Barpeta (16.6%) districts of Assam as a result of top soil erosion due to deforestation and faulty agricultural practices. However, in Tripura, West Tripura district comprises 20.6% of TSA under low soil organic carbon (Fig. 5). High organic carbon is predominant in Nagaland and Sikkim, being declared organic states of NE regions of India, occupying 96.3 and 84.2% of their TSA, respectively.

AESR-wise Spatial Distribution of O.C.

Soil organic carbon was low in 9.0% of TSA covering all the AESRs, in which, maximum area was under AESR 17.2 (11.7% of TSA). High organic carbon was maximum in AESR 16.2 (84.2% of TSA) followed by AESR 17.1 (83.9% of TSA). Abundant forest vegetation and persistence of low temperature are responsible for slow decomposition of organic matter in soils. The agricultural practices are by and large organic in this AESR [3, 17]. These are the major reasons for high organic carbon in soils [32].

Fig. 4 State- and district-wise spatial distribution of soils under pH < 5.5

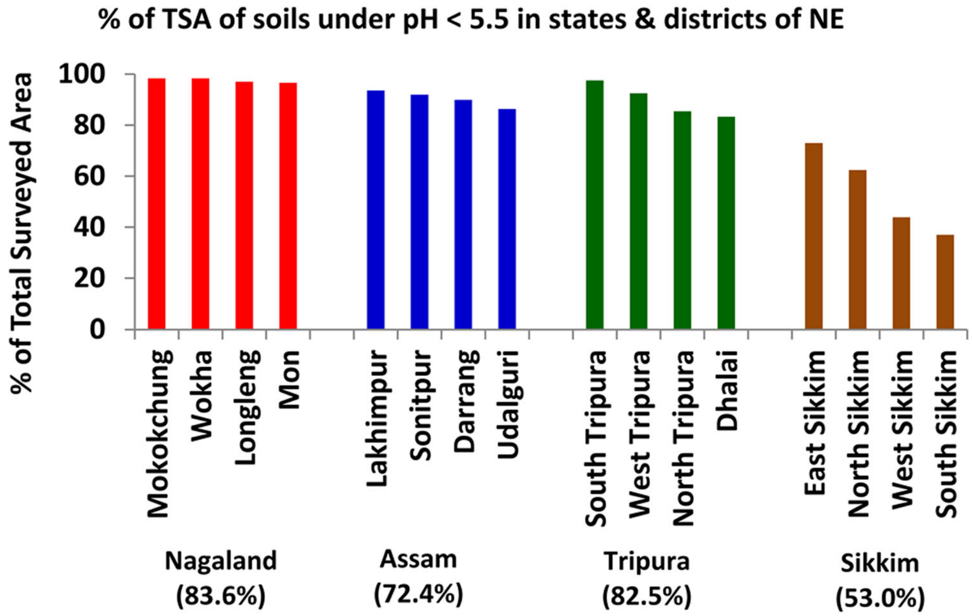
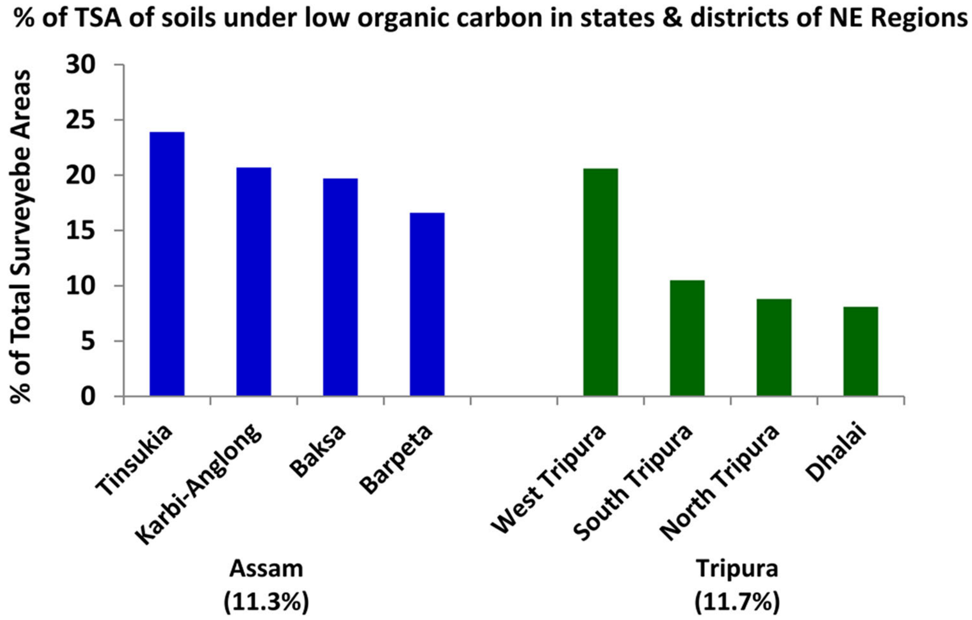


Fig. 5 State- and district-wise spatial distribution of soils under low O.C



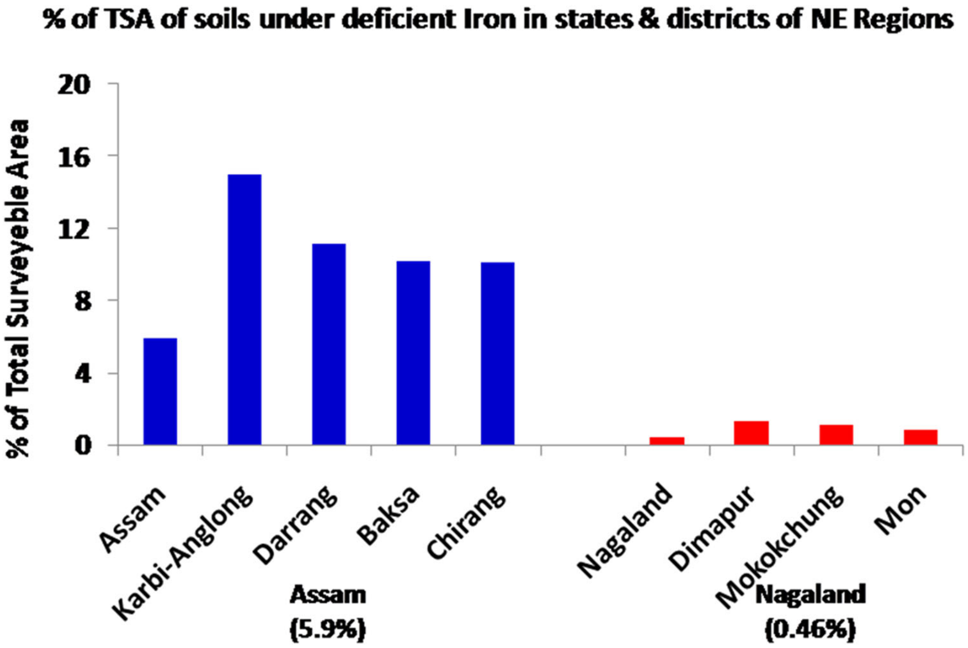
Available Micronutrients in AESRs

Iron (Fe)

State- and District-wise Spatial Distribution of Available Fe: Available Fe was found sufficient in all the districts of Sikkim and Tripura. This was due to the rapid pedogenesis of on highly ferruginous (sandstones and shales) parent materials with heavy rainfall. In Nagaland, only 0.4% of TSA was deficient in available Fe, mostly confined in Dimapur district (1.3% of TSA) due to river bank erosion by Dhansiri, a major tributary of Brahmaputra. In Assam, deficiency of available Fe prevailed in Karbi-Anglong (15.0% of TSA), Darrang (11.0%), Baksa (10.2%) and Chirang district (10.0%) (Fig. 6). These districts are tribal dominated by the major clans as *Karbi* and *Bodo*. Shifting cultivation, locally known as *slash and burn agriculture*, is quite popular in this region. The practice is unscientific and is responsible for forest degradation, soil erosion and loss of fertility status of top soils, which may attribute to micronutrient deficiency at many places of the region [36].

AESR-wise Spatial Distribution of Available Fe: Available Fe was deficient in only 3.8% of TSA of the AESRs, in which maximum area under deficient Fe was noted in AESR 17.1 (6.1% of TSA). However, 90.8% of TSA of the AESRs comprise sufficient available Fe, which

Fig. 6 State- and district-wise spatial distribution of soils deficient in available Fe



may result from high degree of weathering of Fe-rich parent materials of *Tertiary* formations in the region [2, 44].

Manganese (Mn)

State- and District-wise Spatial Distribution of Available Mn: In Tripura, available Mn was sufficient covering all the districts, whereas in Nagaland only 3.9% of TSA was deficient, predominantly in Mon district (7.8% of TSA). In Sikkim, available Mn was deficient in 7.9% of TSA, mostly confined in North Sikkim district (23.3% of TSA). Assam comprises higher Mn deficiency and confined in Tinsukia (23.7% of TSA) and Chirang districts (23.7% of TSA) (Fig. 7).

AESR-wise Spatial Distribution of Available Mn: Available Mn was deficient in 7.6% of TSA of the AESRs, in which maximum area under deficient Mn was noted in AESR 15.4 (10.1% of TSA) followed by AESR 15.2 (9.1% of TSA). Mn deficiency has been observed in both the south and northern banks of Brahmaputra. Soils are occurred in sand casted lands, locally known as “Char lands”. The soils are light textured both at surface as well as at sub-surface horizons from loamy sand to sandy loam, which may not retain the micronutrients. This may attribute to loss on Mn by rapid leaching as well as loss of Mn from top soils due to high run-off due to river bank erosion by Brahmaputra [15].

Zinc (Zn)

State- and District-wise Spatial Distribution of Available Zn: Deficiency of available Zn was found in all the states of NE regions, especially, affecting Assam (35.7% of TSA), followed by Sikkim (15.7%), Nagaland (14.4%) and Tripura (13.6%). In Assam, Zn-deficient soils were mostly occurred in Chirang (76.1% of TSA) and Dhemaji (58.1% of TSA) districts. In Tripura, 34.0% of TSA of North Tripura district comprised soils with deficient zinc. In Nagaland, most Zn-deficient district is Dimapur (25.6% of TSA) (Fig. 8).

AESR-wise Spatial Distribution of Available Zn: Available Zn was deficient in 26.7% of TSA of the AESRs, in which maximum area under deficient Zn was noted in AESR 15.4 (44.4% of TSA). This may be attributed to loss of top soils by river bank erosion, especially in the *Char lands* of upper Brahmaputra valley zone [15].

Copper (Cu)

State- and District-wise Spatial Distribution of Available Cu: Available Cu was deficient in 7.2% of TSA in Assam, 5.0% of TSA of Sikkim and 2.6% of Nagaland. In Tripura, Cu deficiency was not observed. Soils of Tinsukia, Karbi-Anglong and Baksa districts of Assam comprise 23.7, 16.8 and 12.9% of TSA under Cu-deficient status, whereas in East and South Sikkim districts, Cu-deficient soils occupied only 6.2 and 6.1% of TSA and in Mon and Dimapur districts of Nagaland, soils occupied 6.3 and 5.4% of TSA under Cu deficiency (Fig. 9).

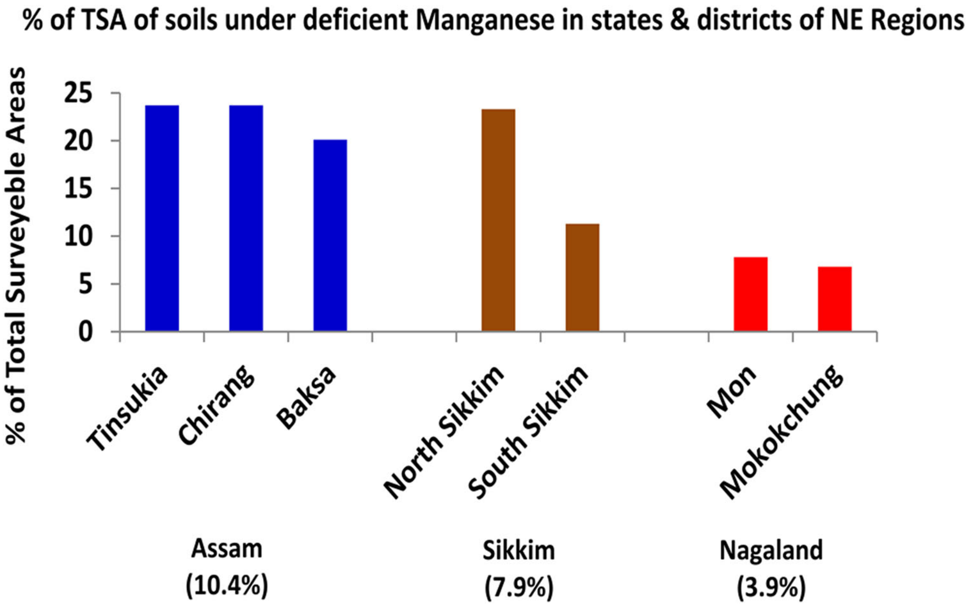


Fig. 7 State- and district-wise spatial distribution of soils deficient in available Mn

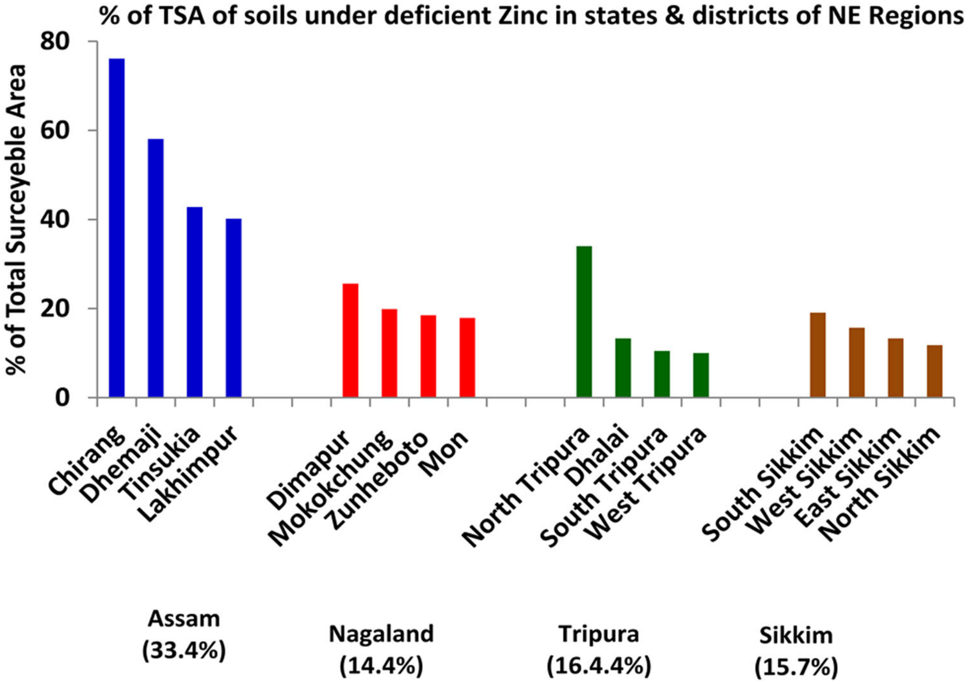


Fig. 8 State- and district-wise spatial distribution of soils deficient in available Zn

AESR-wise Spatial Distribution of Available Cu: Available Cu was deficient only in 4.7% of TSA of the AESRs, in which maximum area under deficient Cu was noted in AESR 15.4 (9.1% of TSA). Similar observations are reported in soils of Manipur [2, 35].

Correlation Studies

Correlation study was made covering all the surveyed districts including four states of NE regions by taking mean values of soil parameters (Tables 6, 7). The results showed that pH had significantly negative correlation with available Fe ($r = -0.28^{**}$), Mn ($r = -0.31^{**}$) and positive correlation with Cu ($r = 0.32^{**}$), whereas organic carbon has significant positive correlation with available Mn ($r = 0.20^{**}$) and Zn ($r = 0.77^{**}$) and negative correlation with Cu ($r = -0.30^{**}$). District-wise 30-year average annual rainfall data of Assam, Nagaland, Sikkim and Tripura [2, 35] were correlated with mean available micronutrients in soils. It was noted that rainfall was significantly correlated with organic carbon ($r = -0.48^{**}$), available Zn ($r = -0.42^{**}$) and Mn ($r = -0.32^{**}$).

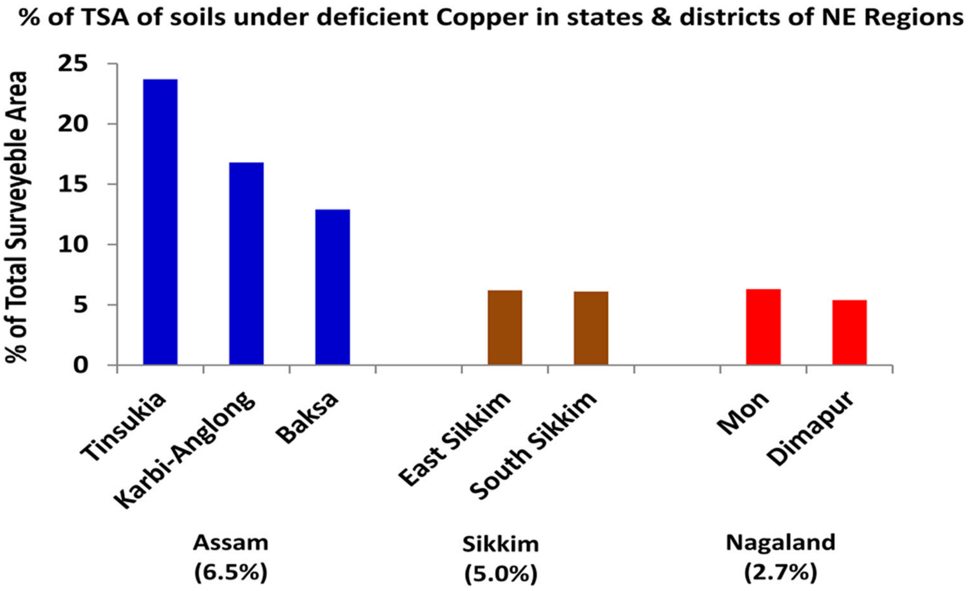


Fig. 9 State-wise spatial distribution of soils under deficient Cu

Rainfall appears to be an important climatic parameter in influencing availability of micronutrients especially, Zn and Mn in soils. Heavy and intense rainfall may cause depletion of soil fertility due to run-off loss occurring in the northern [15] and southern banks of Brahmaputra (AESRs 15.2, 15.3 and 15.4) [9].

Discussions

Soil Reaction (pH)

Systematic information of soil fertility including the deficiency and sufficiency status of micronutrients is very much required to assess the influence of micronutrients on crop growth and overall cropping system of an area. In north-eastern regions of India, information on soil fertility status in relation to crops and cropping systems is sporadic [9, 15, 38]. Our observation bespeaks of spatial distribution of soil fertility status of four states including Assam, Nagaland, Sikkim and Tripura at length. In Assam, soil reaction is one of the major issues of soil fertility constraints as 72.4% of the total surveyed area of the state comprised soils with pH of less than 5.5. The soil acidity constraint is acute in Lakhimpur (93.6% of TSA), Sonitpur (91.9% of TSA), Darrang (89.9% of TSA) and Udalguri (86.3% of TSA) district as also observed in Lakhimpur district of Assam [15]. The development of strongly acidic environment might be attributed to leaching of basic cations due to heavy rainfall, while slightly acidic conditions may be due to recent deposits of alluvial materials.

Organic Carbon

Significant positive correlation was obtained between organic carbon and Mn and Zn due to the formation of soluble organic complexes, especially in AESRs 16.2, 17.1 and 17.2. It is interesting to note that available Cu has positive correlation with soil pH and negatively correlated with organic carbon. This may attribute to a negative impact of organic carbon on available Cu with increasing pH, which has been indicated in this present study. The strong affinity of Cu to organic matter and formation of organo-Cu complexes in a non-available form in soil solution may be accelerated at elevated pH [27, 28], indicating its deficiency in soils. Similar observations have also been reported in soybean–wheat cropping systems in Kumayun region of Himalayas [20].

Available Micronutrients

Low pH may be the reason of sufficiency of available Fe and Mn as evidenced from significant negative correlation of pH with Fe and Mn. A district-level sample survey reported zinc deficiency in 34% of the samples in Golaghat and Jorhat and 23% in Sivasagar district of Assam [9]. We have observed micronutrient deficiency at their spatial distribution in 16 National Food Security Mission (NFSM) districts of Assam, in which zinc deficiency prevailed in the districts of Chirang (76.1% of TSA), Dhemaji (58.1% of TSA), Tinsukia (42.8% of TSA) and Lakhimpur (40.2% of TSA) districts and covered 33.4% of total surveyed area of Assam. Zinc deficiency in soils of Lakimpur district has been reported in earlier observations [15] indicating parity with our observations. Hence, it was obvious from the

Table 6 District-wise rainfalls and soil parameters in AESRs of NE regions

State	AESR	Districts	Average annual rainfall (mm)	Fe	Mn	Zn	Cu
				Mean value in mg kg^{-1}			
Assam	15.4	Tinsukia	2959	94.90	21.50	1.72	4.53
		Lakhimpur	3776	83.90	17.20	0.64	1.21
		Dhemaji	3200	41.10	17.54	0.57	0.92
	15.2	Barpeta	1879	82.90	24.40	0.78	2.39
		Baksa	1637	87.30	23.70	0.80	2.22
		Nalbari	2065	50.80	26.30	0.70	2.21
		Sonitpur	1847	96.50	65.50	0.71	1.85
		Darrang	1590	75.50	16.40	1.93	4.55
		Udalguri	2077	108.40	8.40	0.98	1.74
		Nagaon	1769	109.90	22.00	1.47	4.97
		Marigaon	1860	60.70	18.90	0.56	5.61
	15.3	Bongaongaon	2044	57.50	17.30	0.61	3.27
		Kokrajhar	2826	74.20	10.90	0.57	3.99
		Goalpara	2169	85.30	38.50	1.18	4.24
		Chirang	2826	55.80	11.80	0.53	3.79
	17.1	Karbi-Anglong	1205	78.10	38.80	1.99	2.54
Nagaland	17.1	Dimapur	1120	88.20	51.10	2.31	1.92
		Kohima	1636	65.40	41.40	1.73	1.77
		Peren	1339	51.50	42.70	1.52	1.62
		Wokha	2162	79.90	28.20	1.48	1.03
		Mokokchung	2619	60.70	27.40	1.36	0.86
		Mon	1871	80.90	19.90	1.37	1.56
		Phek	1686	85.30	45.30	1.88	2.65
		Longleng	1395	91.10	27.60	1.76	1.71
		Tuensang	1686	80.00	44.00	2.37	1.46
		Zunheboto	1462	81.50	52.10	2.08	1.91
		Kiphire	1395	78.70	49.90	2.16	1.40
Sikkim	16.2	East Sikkim	2210	65.30	18.00	3.18	2.21
		West Sikkim	1960	65.00	19.30	3.23	2.01
		South Sikkim	1948	58.70	20.10	3.71	2.17
		North Sikkim	2007	65.40	8.20	3.50	1.89
Tripura	17.2	West Tripura	3203	77.60	40.40	0.85	1.25
		South Tripura	2679	119.90	55.50	0.98	1.75
		North Tripura	2698	117.10	36.20	0.90	1.36
		Dhalai	2427	94.10	46.80	1.36	1.23

Table 7 Correlation matrix for soil parameters

Parameters	Rainfall	pH	O.C.	Fe	Mn	Zn	Cu
Rainfall	1.00						
pH	0.001	1.00					
O.C.	− 0.48**	− 0.09	1.00				
Fe	0.002	− 0.28**	− 0.13	1.00			
Mn	− 0.32**	− 0.31**	0.20**	0.34**	1.00		
Zn	− 0.42**	0.09	0.77**	− 0.13	0.007	1.00	
Cu	− 0.09	0.32**	− 0.30**	0.004	− 0.33**	− 0.13	1.00

**Significant at 0.01 *P* level

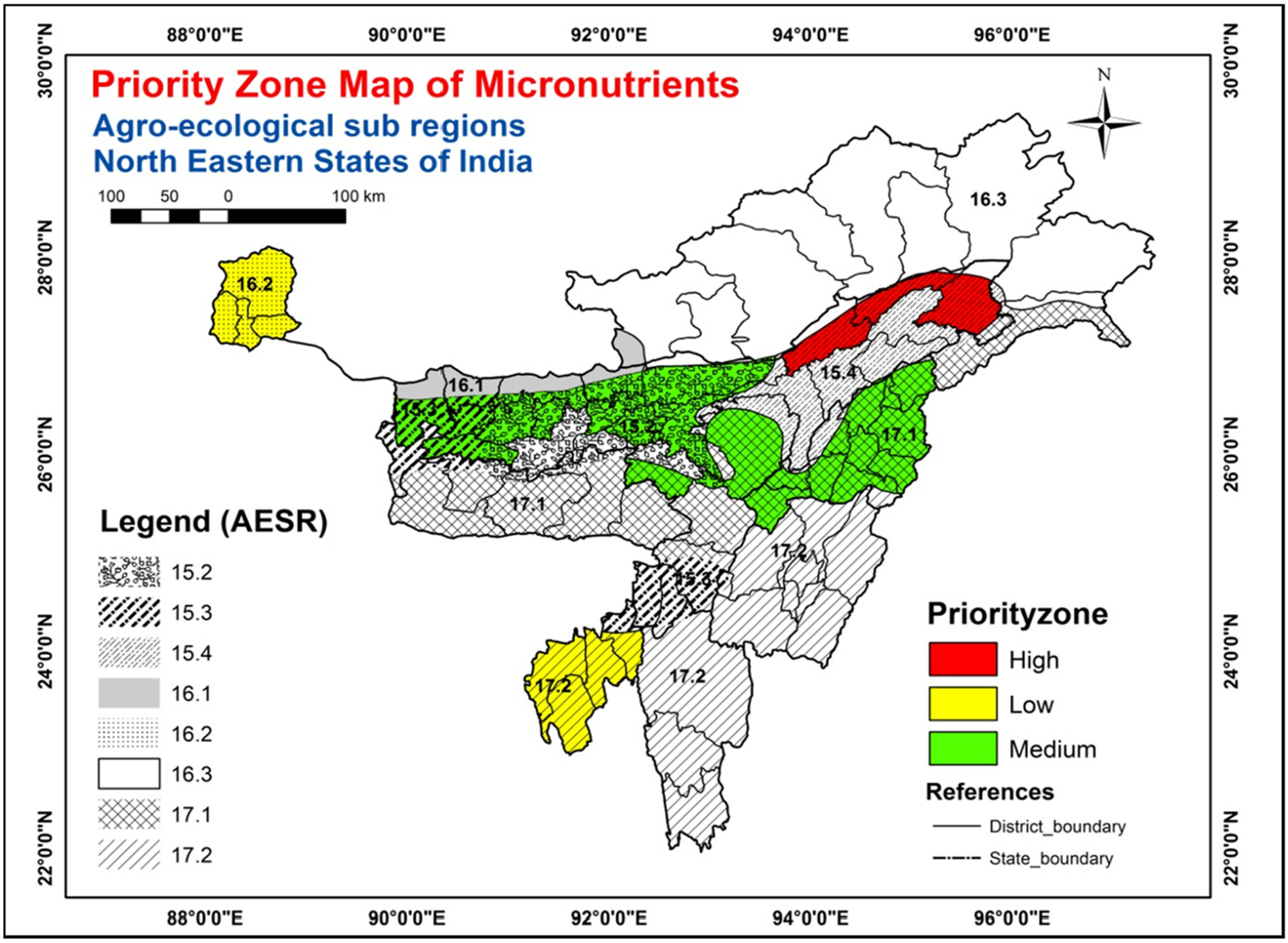


Fig. 10 Priority zone map of micronutrients of soils in AESRs of NE regions of India

Table 8 Priority zoning of micronutrients

AESR	Decision tree with logical query				Composite rank	Priority zoning (range)
	Fe % of TSA under deficient status	Mn	Zn	Cu		
15.2	3.4 (8)	6.7 (6)	30.5 (8)	2.3 (7)	29	Medium (25–35)
15.3	2.7 (7)	9.1 (8)	41.6 (9)	1.1 (6)	30	Medium (25–35)
15.4	3.9 (9)	10.1 (10)	44.4 (10)	9.1 (10)	39	High (> 35)
16.2	0.0 (0)	7.9 (7)	15.7 (6)	5.0 (8)	21	Low (< 25)
17.1	6.1 (10)	9.8 (9)	17.4 (7)	8.1 (9)	35	Medium (25–35)
17.2	0.0 (0)	6.7 (6)	30.5 (8)	2.3 (7)	23	Low (< 25)

research results from our investigations and supported by other researchers that only zinc is the most deficient nutrient in upper Brahmaputra valley zone of Assam [9]. The reason for zinc deficiency may be attributed to its loss due excessive leaching. In north-eastern hilly regions (Karbi-Anglong district of Assam and in Nagaland and Tripura), conventional agricultural practices like *shifting cultivation,* forest fire, etc., results in decline in top soil fertility, which may attribute to zinc deficiency in soils as similar observations are reported in various land use systems of Meghalaya [44] and Manipur [2].The results of the present study indicated that by and large acidity (75.9% of TSA of AESRs of NE states are having acidic soil reaction with pH less than 5.5) and Zn deficiency (26.7% of TSA of

Table 9 Micronutrient priority zones in various AESR of NE regions of India

Priority zone	AESR	State	Districts
Low	16.2	Sikkim	East Sikkim, West Sikkim, South Sikkim and North Sikkim
	17.2	Tripura	West Tripura, South Tripura, North Tripura and Dhalai
Medium	15.2	Assam	Barpeta, Baksa, Nalbari, Sonitpur, Darang, Udalguri, Nagaon and Morigaon
	15.3	Assam	Bangaigaon, Chirang, Goalpara and Kokrajhar
	17.1	Assam	Karbi-Anglong
		Nagaland	All districts
High	15.4	Assam	Tinsukia, Lakhimpur and Dhemaji

AESRs are deficient in available Zn) are the major crop production constraints in the north-eastern region of the country. Heavy rainfall, coarse soil texture (in some cases) and low input agriculture may be attributed as some of the important reasons. Such findings have significant implication on crop production and productivity in north-eastern region of the country. In this backdrop, it is highly relevant to mention that the crop production and productivity of NE regions of the country are lagging much behind the rest of the country, which may be the consequences of soil acidity and Zn deficiency in soils. This derives support from the research findings that soil pH and nutrient leaching are the major yield limiting soil factors [47].

Priority Zoning of Available Micronutrients

Priority zone map of available soil micronutrients has been developed AESR-wise (Fig. 10, Tables 7, 8). AESR 16.2 (all districts of Sikkim) and AESR 17.2 (all districts of Tripura) were low-priority zones. Medium to high organic carbon status under warm to hot per-humid climate may favour bio-release of micronutrients in soil solution. AESR 15.2 (including Barpeta, Baksa, Nalbari, Sonitpur, Darang, Udalguri, Nagaon and Morigaon districts of Assam), AESR 15.3 (including Bangaingaon, Chirang, Goalpara and Kokrajhar districts of Assam) and AESR 17.1 (including Karbi-Anglong district of Assam and all the districts of Nagaland) were attributed to medium priority zone. AESR 15.4 (including Lakhimpur, Dhemaji and Tinsukia districts of Assam) was high-priority zone. High pH and low to medium organic carbon status under hot, humid to per-humid climate may result in decline in availability of micronutrients, especially Zn in AESRs 15.3 and 15.4, and needs immediate attention for fertilizer management. AESR 15.4 is proved to be the most alarming eco-subregion covering Tinsukia, Lakhimpur and Dhemaji districts of Assam and needs immediate attention for micronutrient management (Table 9).

Conclusion

The present investigation envisaged the impact of rainfall, pH and organic carbon on the availability of micronutrients in various AESRs of north-eastern regions of India. Zinc (Zn) deficiency is of serious consequence in AESRs 15.3 and 15.4 followed by manganese (Mn). Heavy and intense rainfall may accelerate leaching loss of Zn and Mn in soils under hot, per-humid climate of north-eastern regions. On the other hand, acidic pH (pH < 5.5) and abundant vegetative cover in AESRs 16.2 (Sikkim), 17.1 (Nagaland) and 17.2 (Tripura) may favour retention of micronutrients in organic fractions of soils, resulting in sufficiency. It was observed that strong soil acidity and zinc deficiency are the two major soil fertility constraints in the NE regions. Soil acidity problem was maximum in Nagaland affecting 83.6% of TSA, whereas zinc deficiency mostly prevailed in Assam (33.4% of TSA). About 44.4% of TSA of AESR 15.4 is affected by zinc deficiency due to loss of top soils by river bank erosion. Based on priority rating, AESR 15.4 appears to have highly vulnerable soil fertility status and needs immediate attention for appropriate measures of soil nutrient management. AESR-based priority zoning may guide the planners as a decision support tool and would help in making efficient fertilizer recommendations in the other remote areas of north-eastern states in the country.

Acknowledgements The authors gratefully acknowledge the past and present Directors, ICAR-NBSS&LUP, Dr. U. Baruah and Dr. K.D. Sah, former Heads, ICAR-NBSS&LUP, Regional Centre, Jorhat, Assam and Dr. D.C. Nayak, Head, ICAR-NBSS&LUP, Regional Centre, Kolkata for extending their kind support and all possible help in this endeavour.

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