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UNDERSTANDING SPATIAL VARIABILITY OF SOIL PROPERTIES AND REGIONAL DELINEATION USING SOIL FERTILITY INDICES- A STUDY OF HIMACHAL PRADESH

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ABSTRACT

The study aims to delineate spatially homogenous regions in Himachal Pradesh based on soil fertility indices for better fertilizer recommendation and soil health. The imbalance score findings confirmed continued excessive use of fertilizers, particularly for nitrogen and phosphorus. Nutrient index values derived using the secondary data from SHC MIS showed nitrogen and sulphur levels range from low to medium and phosphorus, potassium, organic carbon from medium to high, with no major deficiencies reported for micronutrients. No salinity was detected and neutral soil pH was reported. K-means clustering distributed districts into four and three clusters based on macronutrient and three micronutrient indices, respectively. This delineation indicated the variability in the nutrient status of the soil in the state demanding region-specific policies. Development of region-specific nutrient maps and localized fertilizer policies is suggested.
***Keywords* :** Soil fertility Index, NIV, K-means clustering, CSFI, Soil Health Card.

Introduction

The role of fertilizer in enhancing crop productivity and safeguarding food security is well-established since the green revolution (Hopper 1993; Daberkow *et al*., 2000; Alexandratos and Bruinsma, 2012; McArthur and McCord 2017; Majumder 2023). But there are also numerous problems associated with fertilizers such as imbalanced use, poor fertilizer response, low crop productivity and continuous land degradation (Chand and Pandey, 2009; Shukla *et al*., 2014; Chand and Pavithra 2015; Reddy 2018; Wu *et al*., 2018; Cheng *et al*., 2019). There has been an overuse of fertilizers, specifically nitrogen, often at the expense of micro-nutrients and organic manure. For sustainable profitability the base is soil health and fertility and the first stage towards this direction is to follow the optimum fertilizers application and cropping pattern based on the scientific recommendations. Keeping this problem into consideration, the Government of India announced Soil Health Card Scheme across the country on 5th December, 2015 with a more focused attempt to ensure soil management at farmer's level. The purpose was to make each farmer aware about the nutrient status of the soil of their landholding and guide them on fertilizer recommendations, soil amendments and suitable crops that are needed to sustain soil health and profitability in the long run (Makadia 2017; Reddy *et al*. 2018). Given the considerable variation in soil fertility across the country, formulating location-specific guidelines can help identify and correct micro-level imbalances through balanced fertilizer application (Niranjana *et* *al*., 2018; Patel *et al*., 2019; Sachan and Krishna, 2022; Ankhila *et al*., 2023). The study focuses on to make use of the data from SHC MIS (Soil Health Card Management Information System) to depict the soil fertility status of the state in order to provide suggestions for the state-run machinery to identify the nutritional status and construct indices that will assist in making region specific fertilizer recommendations preventing overuse and soil degradation.

Material and Methods

Spatial variability of soil properties using Nutrient index approach

To understand the spatial variability of soil properties in Himachal Pradesh based on soil fertility indices, nutrient index approach was used (Parker *et al*., 1951, Singh *et al*., 2016, Niranjana *et al*., 2018). The individual nutrient indices and composite indices were developed using the state-wise nutrient status data from SHC MIS (Soil Health Card Management Information System), Ministry of Agriculture and Farmers Welfare. The data of SHC MIS for 2 calendar years, i.e., 2023 and 2024 were collected for the various soil parameters for all the districts of Himachal Pradesh.

The NIV for all the 12 parameters, viz., N, P, K (Primary macro-nutrients); S (Secondary-macronutrient); Zn, Fe, Cu, Mn, Bo (Micro - nutrients); and pH, EC, OC (Physical parameters) was computed using the following formulae.

The formula for parameters N, P, K, S and OC was based on scores given in the range of 1 to 3 for low, medium and high categories, respectively:

$$Q_g = \frac{N_h*3+N_m*2+N_l*1}{N_h+N_m+N_l}$$

Where,

Q_g = Nutrient Index Value (NIV) for N, P, K, S and OC

N = number of samples

h = high

m= medium

l= low respectively

g = N, P, K, S and OC

For parameters B, Zn, Ca, Fe, Mn scores of 1 and 2 were used, representing deficient and sufficient categories, respectively. For Electrical Conductivity (EC) scores of 1 and 2 were used, representing non-saline and saline categories, respectively:

$$Q_h = \frac{N_s*2+N_d*1}{N_s+N_d}$$

Where,

Q_h =Nutrient Index Value (NIV) for B, Zn, Ca, Fe, Mn and EC

N = number of samples

s= sufficiency/ saline

d= deficiency/ non-saline

h = B, Zn, Cu, Fe, Mn and EC

For pH, the scores are given as:

If pH is >7.5 (Alkaline), then score = 3

If pH is 7.0 ± 0.5 (Neutral), then score = 2

If pH <6.5 (Acidic), then score = 1

$$Q_i = \frac{N_{al}*3+N_n*2+N_{ac}*1}{N_{al}+N_n+N_{ac}}$$

Where,

Q_i = Nutrient Index Value (NIV) for pH

N = number of samples

al = Alkaline

n = Neutral

ac = Acidic

Finally, using individual nutrient index values, composite soil fertility indices (Macronutrient index, Micronutrient index and Total nutrient index) were computed using following formula:

$$CSFI_j = \sum_{i=1}^{n} \frac{NIV_i}{n}$$

Where,

$CSFI_j$ = composite soil fertility index

j = Macronutrient index, Micronutrient index and Total nutrient index

NIV_i = Individual Nutrient Index Values

i = number of parameters (i = 1,2, 3…. n)

n = total number of parameters

Finally, the districts were classified into different clusters using K-means clustering approach based on CSFI values, Macronutrient index, Micronutrient index.

Determining the clustering tendency of the dataset

The first step in the clustering techniques is to determine the clustering tendency of the dataset (Adolfsson, 2019). This is so because the major problem in cluster analysis is that clustering techniques can assign clusters to dataset even if there is spatial randomness in the data (Banerjee and Dave, 2004, Hayatu *et al*., 2020, Wright, 2022). Therefore, it is important to check the feasibility of clustering whether the data contains significant clusters or not (Han *et al*., 2012, Adolfsson, 2019). For this purpose, Hopkins statistics was used to measure the probability of spatial randomness in data (Banerjee and Dave, 2004, Li *et al.,* 2018, Adolfsson, 2019, Hayatu *et al*., 2020, Wright, 2022). It was done by using function hopkins in Hopkins package in R (Wright, 2022).

The Hopkins statistic is represented by H and its value lies in the range of 0 to 1 (Hopkins and Skellam, 1954). The interpretation of Hopkins statistic (H) as per the guidelines given by Lawson and Jurs 1990 is as follows:

a) Low values of H (H<0.5) indicate repulsion of the events from each other

b) Values of H near 0.5 indicate spatial randomness of the events

c) Values of H > 0.75 indicate a clustering tendency in the data

Determining the optimal number of clusters (k):

The methods used in the study are Elbow method and Gap statistic method. The study was done by using factoextra package in R (version 1.0.7) (Kassambara and Mundt, 2016). Elbow technique considers the total intra-cluster variation or total within-cluster sum of squares (WSS) as a function of the number of clusters (Syakur *et al*., 2018). The optimum cluster number (K) is where sharp bend in the curve occurs or that point after which adding more clusters doesn't significantly reduce the within-cluster sum of squares (WSS). Gap Statistics techniques compares total within cluster variation for multiple k values with the average values under the data distribution of null point. The optimum cluster count (K) is typically selected as the smallest K where the gap statistic reaches its maximum value or the point just before the gap statistic starts to decline substantially (Charrad *et al*., 2014).

K-means clustering: After determining the optimum cluster count k, each cluster is denoted by its centroids. All remaining items are allocated to their near centroids on the basis of Euclidean Distance Metric. Following this, the algorithm computes the new average of each cluster. All the items are reallocated using the updated cluster means. This cluster allocation and centroid update stages are repetitive till the cluster allocations stop to vary (Hooman *et al*., 2015).

Results and Discussion

Imbalance in fertilizer application

Figure 1 illustrated the deviation in fertilizer usage from the ideal N:P: K norm of 4:2:1 in India from 1961-2021. Since the 1960s, nitrogen (N) consumption showed significant fluctuations throughout the period, with noticeable peaks in the mid-1990s and a sharp dip around 2010 before rising again. The peak in 1990s was attributed to the liberalization, controlled prices of Urea and fertilizer subsidies whereas the movement towards the balance and the dip in late 2000s accrued to the implementation of Nutrient Based Subsidy scheme. Phosphorus (P) application showed a steady trend, exceeding the ideal norm in the mid-1980s, reaching balanced usage at certain points, and occasionally exceeding the recommended norm. Unlike nitrogen and phosphorus, potassium has often been either minimally applied or entirely overlooked, primarily due to its higher cost, entire dependence on imports and limited awareness among farmers (Anonymous 2022-23). The results were consistent with the findings of Chand and Pavitra (2015) and Kumar *et al*., 2022.

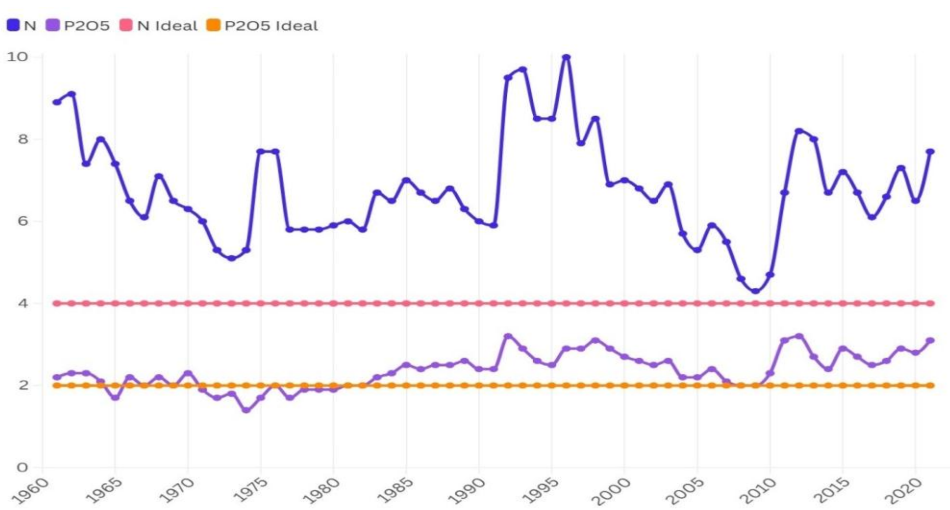

Fig. 1 : Imbalance trends in nutrients usage from ideal ratio of 4:2:1 (N: P_2O_5:K_2O)
(Source: Based on the author's calculations using data from Fertilizer Statistics, FAI.)

The imbalance score examines the deviation between actual fertilizer use and the recommended levels, where a perfect balance yields an imbalance score (I) of 0 and values of I greater than zero indicate divergence from the ideal N:P: K ratio of 4:2:1. The imbalance score value was above 3 in the liberalization period (1990s) reflecting substantial overuse of nitrogen, particularly contributed by urea, and to some extent phosphorus. Post-liberalization the imbalance scores declined, suggesting a gradual shift toward more balanced fertilizer application, reaching a low point in 2010 with a score of 0.32. However, post-2010, the imbalance score began to rise slightly again reaching 2.22 in 2021-22 which could be associated with the policy changes such as the deregulation of fertilizer pricing and the implementation of the Nutrient-Based Subsidy (NBS) scheme, which excluded urea, potentially contributing to renewed imbalance (figure 2).

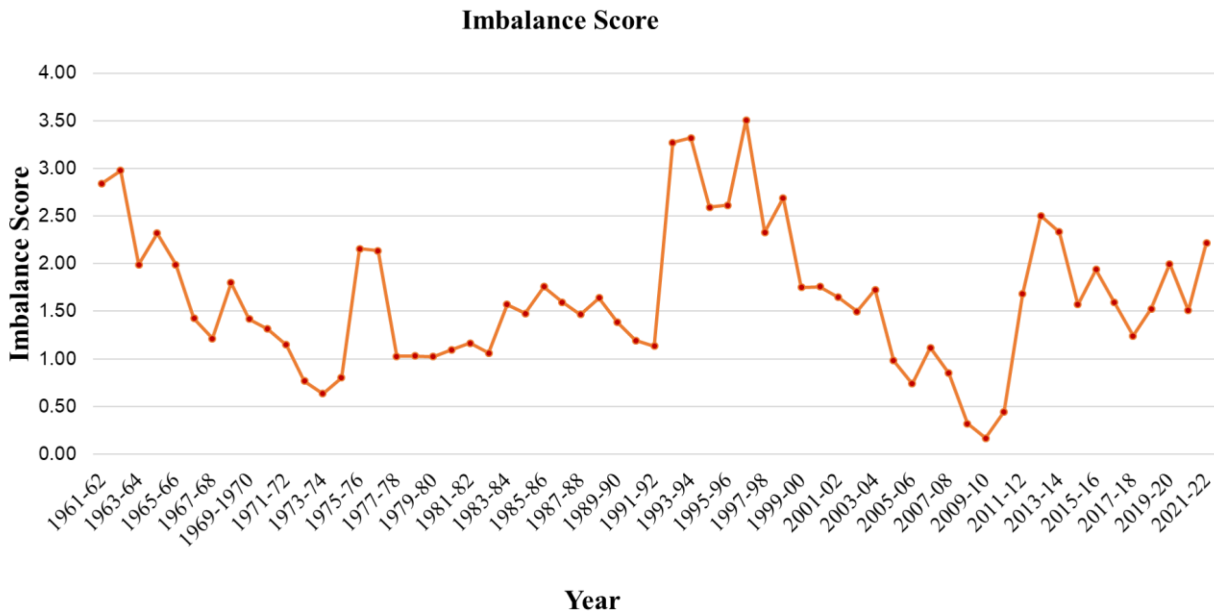

Fig. 2 : Trend of nutrient imbalance scores at the national level from 1961 to 2021
(Source: Based on the author's calculations using data from Fertilizer Statistics, FAI.
Spatial Variability of soil properties and delineation of homogenous regions Coverage of Soil Health Card scheme)

The district-wise data of Soil Health Card scheme showed that out of the total samples collected 92.51 percent of the samples have been tested and Soil health card have been generated (table 1). The highest number of soil sample collection was from district Kangra (14426) and Mandi (12431). The SHC generated data showed tha Kinnaur stands at the top with 100 percent of the samples have been tested and SHCs created followed by Sirmaur (97.10%) and Solan (95.03%).

Table 1: District-wise Soil Health Card data for 2023 and 2024

District	Samples Collected (No.)	SHC Generated	%
Bilaspur	6554	5981	91.26
Chamba	5928	5499	92.76
Hamirpur	6633	6234	93.98
Kangra	14426	13040	90.39
Kinnaur	1683	1683	100.00
Kullu	6724	6325	94.07
Lahul and Spiti	1582	1483	93.74
Mandi	12431	11090	89.21
Shimla	8808	8194	93.03
Sirmaur	7167	6959	97.10
Solan	7184	6827	95.03
Una	7331	6664	90.90
Himachal Pradesh	86451	79979	92.51

(Source: Based on the author's calculations using data from SHC-MIS portal.)

Nutrient index value

The nutrient index value data were categorized into three categories for N, P, K, S, OC (Low, Medium, High) and pH (Acidic, Neutral, Alkaline) and into two categories for B, Fe, Zn, S, Cu (Sufficient, Deficient) and EC (Saline, Non-saline) using Equal Interval method (Parker *et al*. 1951, Singh *et al* 2016, Niranjana *et al*. 2018) (Table 2).

Table 2: Categories of NIV with respective range and remarks for different parameters

Nutrient Index Value (NIV)	Range	Remarks	
		N, P, K, S, OC	pH
I	Below 1.67	Low	Acidic
II	1.67-2.33	Medium	Neutral
III	Above 2.33	High	Alkaline
Nutrient Index Value (NIV)	**Range**	**Remarks**	
		B, Fe, Zn, S, Cu	EC
I	<1	Deficient	Non-Saline
II	>1	Sufficient	Saline

Macronutrients, Organic Carbon and pH

District-wise soil nutrient index values for macronutrients (Primary-Nitrogen, Phosphorus, Potassium; Secondary–Sulphur), Organic Carbon (OC) and pH were computed (Appendix 1). Nitrogen levels falls under low and medium categories in the state. Out of 12 districts only four districts, Hamirpur, Solan, Lahul & Spiti, and Bilaspur had medium range of Nitrogen, rest fell under the low category (figure 3). Phosphorus levels vary from medium to high ranges in the state. Una, Sirmaur, Kullu had high Phosphorus levels while the remaining 9 districts fall under the medium range category (figure 3). The potassium levels also fell under medium and high category. Out of 12 districts only five districts (Hamirpur, Kangra, Kinnaur, Kullu and Sirmaur) had high level of Potassium in the soil (figure 3). The Sulphur levels in the soil fell under low and medium ranges in the state. Only three districts (Bilaspur, Chamba and Mandi) had low Sulphur levels in the soil and the remaining districts have medium level of Sulphur in the soil (figure 3). Additionally, the state had high level of organic carbon except for two districts, Bilaspur and Shimla which falls under medium category (figure 5). The soil pH of all the districts in Himachal fell in the neutral range (6.5-7.5) (figure5).

Micronutrients and Electrical Conductivity

District-wise soil nutrient index values for micronutrients (Copper, Boron, Iron, Zinc, Manganese) Electrical Conductivity (EC) are computed (Appendix 2). The nutrient index values for all micronutrients (Copper, Boron, Iron, Zinc, Manganese) for all the districts of Himachal Pradesh showed that all the micronutrients fall under sufficient category in each district (figure 4). Additionally, the salinity status of the soil was non-saline for all the districts as shown by the Electrical Conductivity index (Q_{EC}) (figure 5).

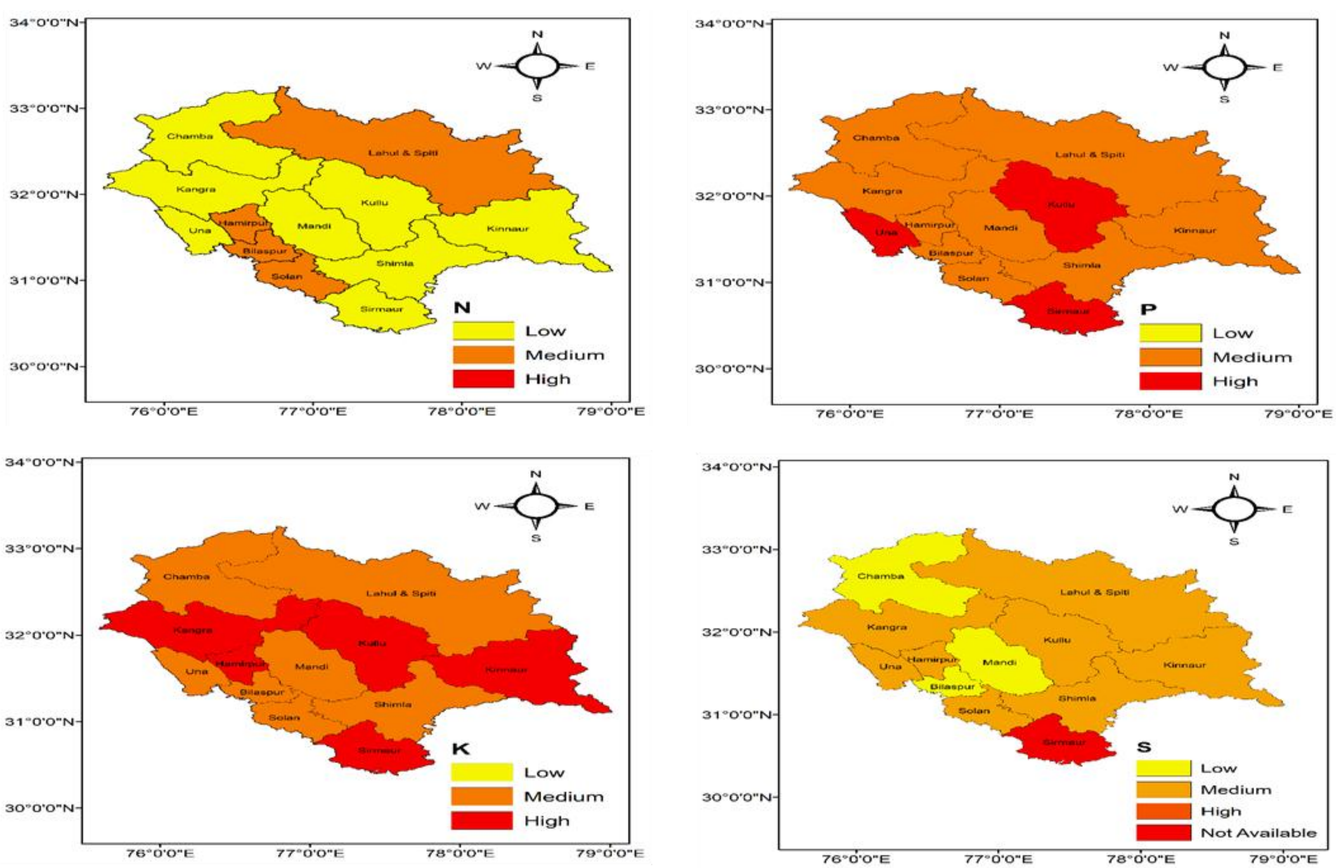

Fig. 3: Pictorial representation of NIV of macronutrients (N,P,K,S) for all the ditricts of Himachal Pradesh (Source: Based on Author's calculations using data from SHC-MIS portal)

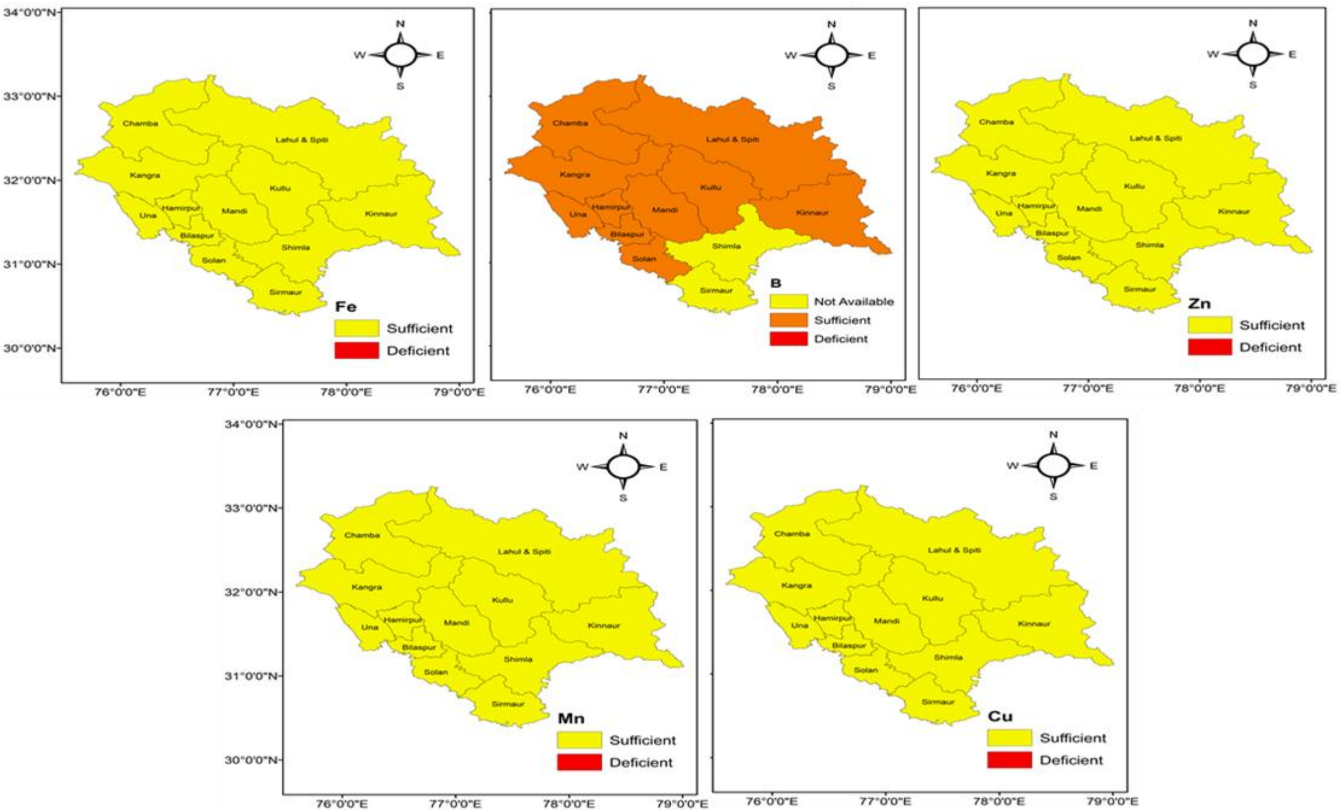

Fig. 4: Pictorial representation of NIV of micronutrients (Fe,B,Zn,Mn,Cu) for all the districts of Himachal Pradesh (Source: Based on Author's calculations using data from SHC-MIS portal)

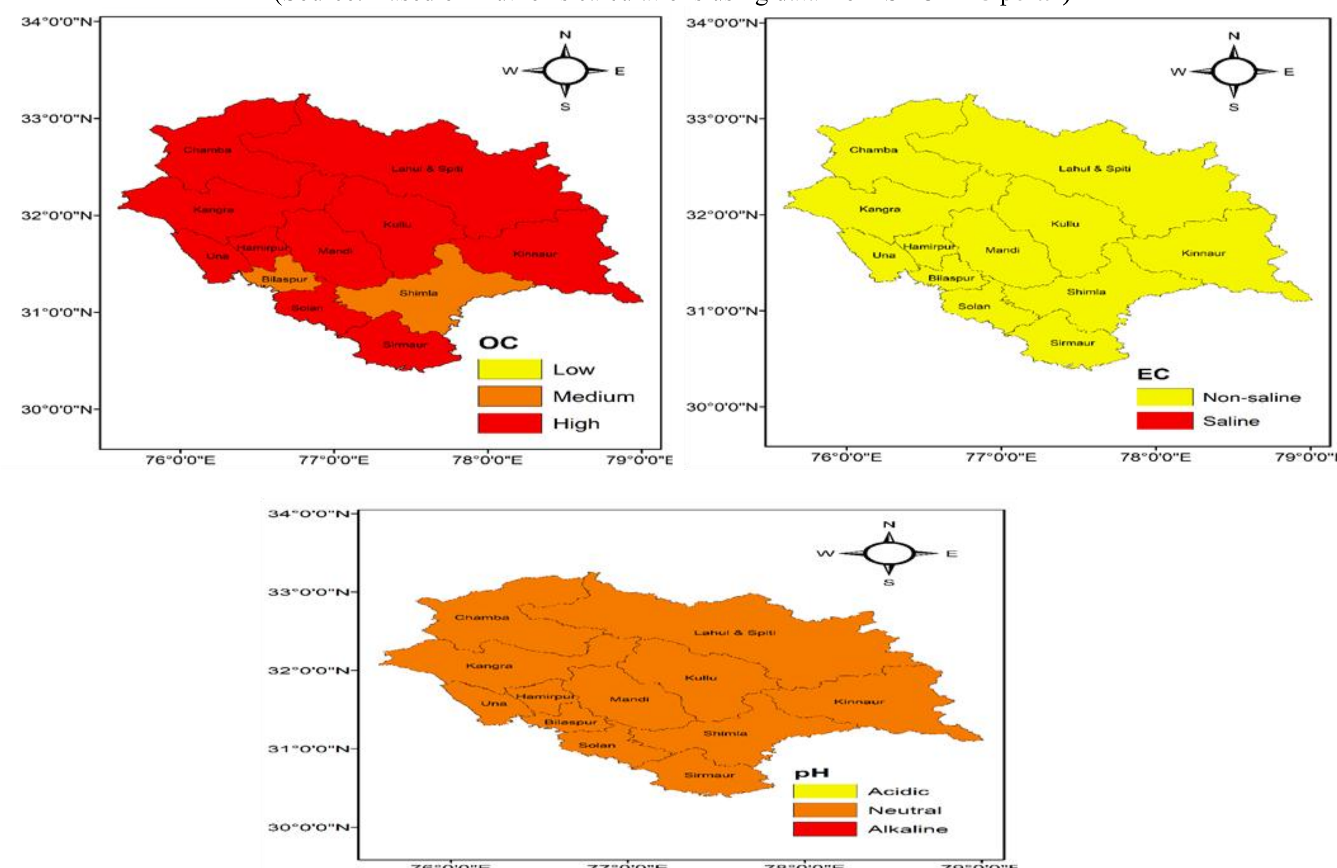

Fig. 5: Pictorial representation of NIV of Physical parameters (OC,pH,EC) in all the districts of Himachal Pradesh (Source: Based on Author's calculations using data from SHC-MIS portal)

Finally, Soil fertility indices: Macronutrient index and micronutrient index were constructed (Table 4). On the basis of these indices the districts were delineated into different clusters of spatial homogeneity using K-means clustering approach.

Table 3: District-wise Soil fertility indices

District	Macronutrient Index	Micronutrient index
BILASPUR	1.75	1.98
CHAMBA	1.71	1.96
HAMIRPUR	2.11	1.85
KANGRA	1.99	1.95
KINNAUR	2.12	2.00
KULLU	1.99	1.93
LAHUL AND SPITI	1.84	1.87
MANDI	1.68	1.97
SHIMLA	1.85	1.50
SIRMAUR	1.70	1.60
SOLAN	2.03	1.98
UNA	1.96	1.96

The results of clustering tendency using Hopkins statistic show that the macronutrient index dataset is highly clustered (H=0.79) with significant clusters (p value <0.05). Micronutrient index datas*et al*so consists of significantly clustered data with Hopkins statistic (H) is 0.77 (p value <0.05) (Table 5).

Table 4: Clustering Tendency of the Dataset

Index	Null hypothesis	Hopkins statistic (H)	p value	Result
Macronutrient Index	There is spatial randomness in data	0.79	0.001	Clustered data
Micronutrient Index		0.77	0.004	Clustered data

The optimal number of clusters are determined using Elbow method and Gap statistic method. The results show that the Elbow method (figure 6) and Gap statistic (figure 7) provide an optimal count of four clusters for the macronutrient index dataset. Figure 8 and 9 show that the Elbow method and Gap statistic provide an optimal count of three clusters for the micronutrient index dataset.

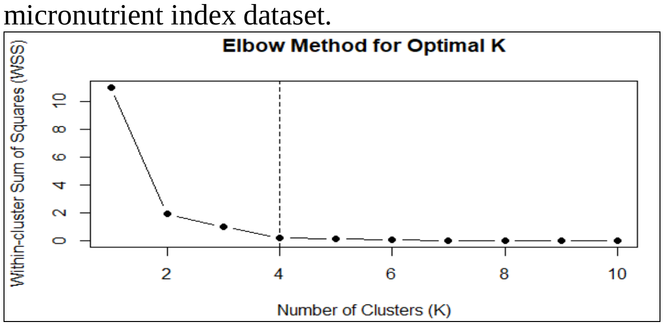

Fig. 6: Optimal number of clusters using Elbow method based on Macronutrient Index

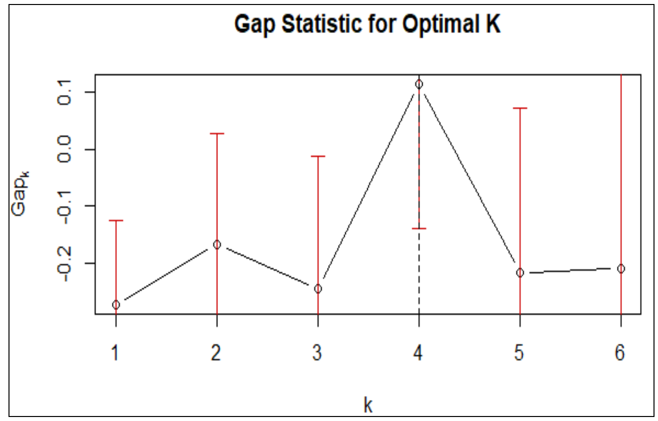

Fig. 7: Optimal number of clusters using Gap statistic based on Macronutrient Index

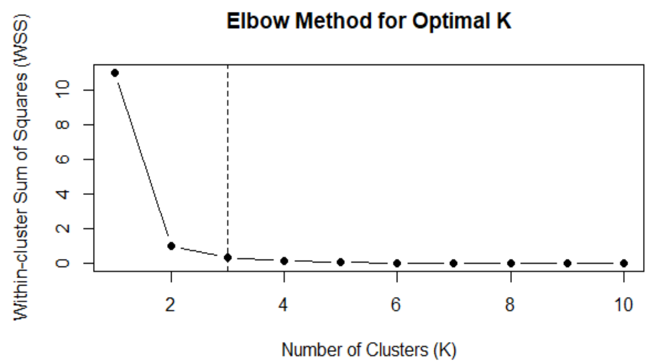

Fig. 8: Optimal number of clusters using Elbow method based on Micronutrient Index

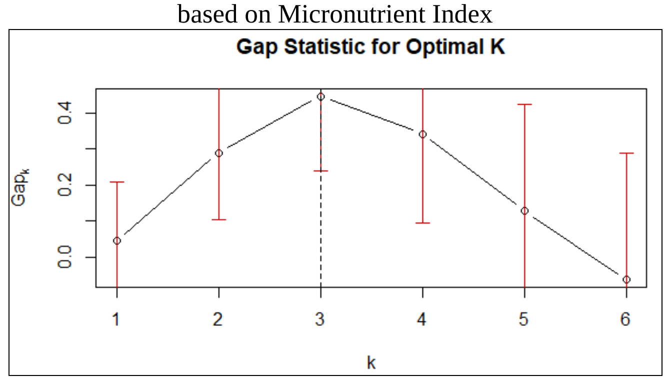

Fig. 9 : Optimal number of clusters using Gap statistic based on Micronutrient Index

The K-means clustering based on the macronutrient index distributes the districts into four clusters (figure 9). Cluster I comprises of Bilaspur, Chamba, Mandi and Sirmaur with cluster mean value is 1.71. Cluster II consists of Shimla and Lahual & Spiti districts with cluster mean value is 1.85. Kangra, Kullu, Solan and Una falls under cluster III with meann value of 1.99. The residual districts Hamirpur and Kinnaur came under cluster IV with cluster mean 2.11.

The K-means clustering based on the micronutrient index divided the districts into three clusters (figure 10). Cluster I comprised of Shimla and Sirmaur with cluster mean value is 1.55. Cluster II consisted of Hamirpur and Lahual & Spiti districts with cluster mean value is 1.86. The districts Bilaspur, Chamba, Kangra, Kullu, Mandi Solan, Kinnaur and Una fell under cluster III with mean value of 1.97.

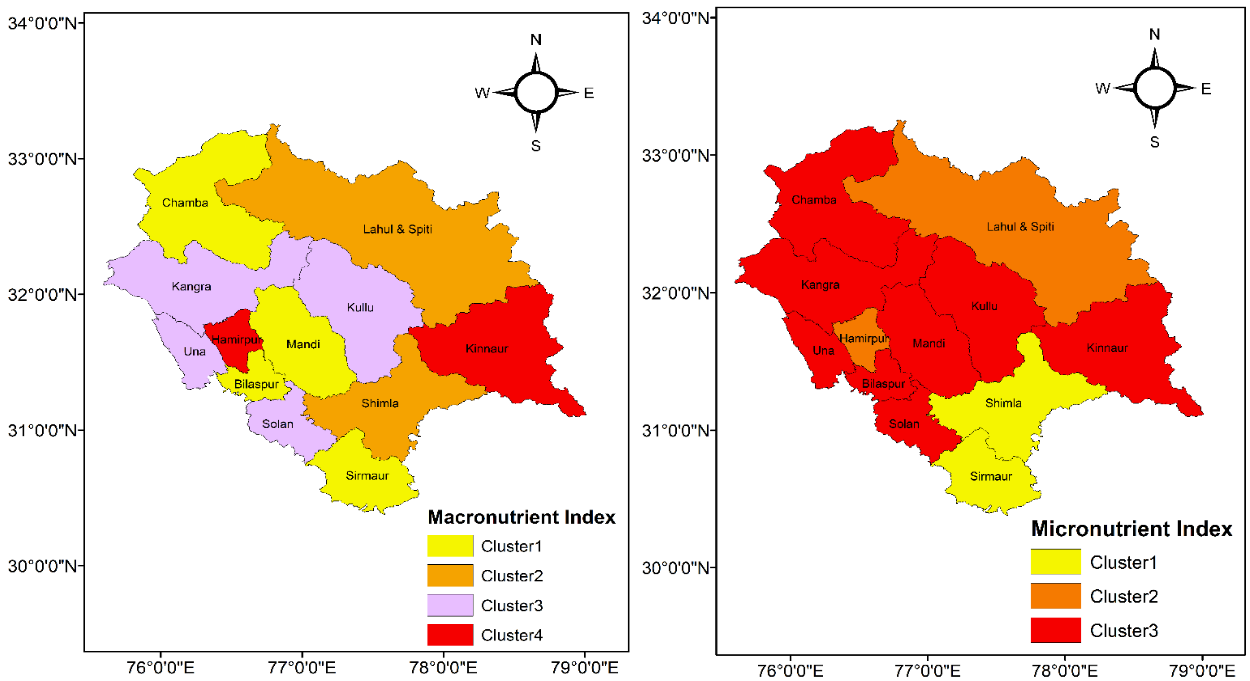

Fig. 10: Pictorial representation of K-means clustering of districts of Himachal Pradesh based of Macronutrient Index and Micronutrient Index
(Source: Based on Author's calculations using data from SHC-MIS portal)

Conclusions

The individual nutrient index values showed that Nitrogen and Sulphur ranges from low to medium and Phosphorus Potassium and Organic Carbon ranges from medium to high values. No micronutrient deficiency and salinity were reported in any district. Additionally, pH lies in the neutral range. The K-means clustering based on the composite indices that were macronutrient and micronutrient index distributed the districts into four and three clusters, respectively. Thus, indicating regional variation in soil nutrient status of the state. The study recommends that region specific nutrient map should be constructed which could be extended from district to block and to further villages using secondary data for making region-specific localized fertilizer policy.

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Conflict of interest

There is no conflict of interest among authors.

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Appendix:

Table 1 : District-wise NIV for macronutrients, Organic Carbon and pH

District	Q_N	Remarks	Q_P	Remarks	Q_K	Remarks	Q_{OC}	Remarks	Q_S	Remarks	Q_{pH}	Remarks
Bilaspur	1.91	**M**	1.87	M	1.91	M	1.91	**M**	1.33	**L**	2.00	N
Chamba	1.12	L	1.91	M	2.26	M	2.81	H	1.55	**L**	1.98	N
Hamirpur	1.78	**M**	2.18	M	2.50	**H**	2.83	H	1.99	M	2.00	N
Kangra	1.13	L	2.22	M	2.61	**H**	2.92	H	2.00	M	1.99	N
Kinnaur	1.54	L	2.26	M	2.67	**H**	2.80	H	2.00	M	1.98	N
Kullu	1.00	L	2.74	**H**	2.35	**H**	2.93	H	1.88	M	1.97	N
Lahul & Spiti	1.85	**M**	1.83	M	1.69	M	2.99	H	2.00	M	2.00	N
Mandi	1.05	L	2.21	M	2.14	M	2.71	H	1.33	**L**	1.98	N
Shimla	1.65	L	1.88	M	1.86	M	1.89	**M**	2.00	M	1.99	N
Sirmaur	1.24	L	2.60	**H**	2.95	**H**	2.96	H	0.00	NA	2.00	N
Solan	1.82	**M**	2.17	M	2.13	M	2.51	H	1.99	M	2.00	N
Una	1.30	L	2.39	**H**	2.20	M	2.38	H	1.95	M	2.00	N

Note: $Q_{N,}$ $Q_{P,}$ $Q_{K,}$ $Q_{OC,}$ $Q_{S,}$ Q_{pH} represent nutrient index value (NIV) for Nitrogen, Phosphorus, Potassium, Organic Carbon, Sulphur and pH. L- low, M-Medium, H- High; N- Neutral
Source: Based on Author's calculations using data from SHC-MIS portal

Table 2: District-wise nutrient index value for micronutrients and Electrical conductivity.

District	Q_{Cu}	Remarks	Q_B	Remarks	Q_{Fe}	Remarks	Q_{Zn}	Remarks	Q_{Mn}	Remarks	Q_{EC}	Remarks
Bilaspur	2.00	S	2.00	S	1.97	S	1.96	S	1.99	S	1.00	NS
Chamba	1.98	S	2.00	S	1.97	S	1.91	S	1.92	S	1.00	NS
Hamirpur	1.99	S	2.00	S	1.99	S	1.92	S	1.36	S	1.00	NS
Kangra	1.98	S	1.99	S	1.98	S	1.97	S	1.83	S	1.00	NS
Kinnaur	2.00	S	2.00	S	2.00	S	2.00	S	2.00	S	1.00	NS
Kullu	1.97	S	1.99	S	1.95	S	1.95	S	1.80	S	1.01	NS
Lahul & Spiti	2.00	S	2.00	S	1.98	S	1.99	S	1.37	S	1.00	NS
Mandi	1.99	S	2.00	S	1.93	S	1.97	S	1.95	S	1.03	NS
Shimla	1.99	S	NA	NA	1.94	S	1.90	S	1.67	S	1.00	NS
Sirmaur	2.00	S	NA	NA	2.00	S	2.00	S	1.99	S	1.00	NS
Solan	1.99	S	2.00	S	1.97	S	1.96	S	1.96	S	1.00	NS
Una	1.99	S	2.00	S	1.98	S	1.96	S	1.89	S	1.01	NS

Note: $Q_{Cu,}$ $Q_{B,}$ $Q_{Fe,}$ $Q_{Zn,}$ $Q_{Mn,}$ Q_{EC} represent nutrient index value (NIV) for Copper, Boron, Iron, Zinc, Manganese and Electrical Conductivity. S- Sufficient, D- Deficient, NA- Not Available, NS- Non-saline
Source: Based on Author's calculations using data from SHC-MIS portal