Original Research Article

Farm-scale mapping of soil phosphorus and potassium fractions using geostatistical technique

Abstract:

Phosphorus (P) and potassium (K) are two major nutrients for agricultural productivity and sustainability. The spatial variability mapping of soil phosphorus and potassium content in surface soils collected through grid sampling technique were developed using geo-spatial technology for Indian Council of Agricultural Research -Indian Agricultural Research Institute (ICAR-IARI) farm, New Delhi, India. Soil available P content ($NaHCO_3$-P) and P-fractions such as NaOH extractable-P (NaOH-P), citrate-bicarbonate extractable P (CB-P), citrate-bicarbonate-dithionite extractable-P (CBD-P) and HCl extractable-P (HCl-P) through sequential fractionation techniques and K fractions (available-K and non-exchangeable-K) were estimated. In geostatistical technique, exploratory data analysis and semivariogram analysis for P & K fractions were conducted and ordinary kriging was used for spatial interpolation and mapping. On average basis, among the P-fractions, Ca-bound phosphorus (HCl-P) had highest value followed by non-occluded Fe- and Al-bound-P (*i.e.* NaOH-P) and occluded-P within iron oxide and hydrous oxide (*i.e.* CBD-P). Soil available K in the farm ranged from 43.9 to 839.3 mg kg^{-1} and non-exchangeable-K content was high to very high level (820-1921 mg kg^{-1}). Among P & K fractions, occluded-P and Ca-bound P showed first order polynomial surface trend, which were removed before ordinary kriging interpolation. Semivariogram analysis of soil P- & K-fractions at the farm indicated the effective spatial range with level of spatial dependency. Prediction map of P- & K- fractions in the semiarid agricultural farm thorough ordinary kriging were found superior to log-normal ordinary kriging. The map based fertilizer recommendation and management practices for major cropping systems in the farm are crucial for precision nutrient management and sustainable agriculture.

Keywords: Ca–bound phosphorus, Non-occluded phosphorus, Occluded phosphorus, non-exchangeable potassium, Geo-statistics, Spatial variability mapping

1. Introduction:

Phosphorus (P) and potassium (K) are second and third major essential plant nutrients respectively for crop growth and productivity. The distribution and forms of soil P and K nutrients provide key information for assessing its availability and degree of chemical weathering of soils (Sarkar et al., 2014; Singh et al., 2003). Besides, inorganic P fractionation is useful criteria to characterize the fate of P sources alongwith its potential availability and mobility in different soil types (Mostashari et al., 2008). Residual soil P and K fertility build-up on indiscriminate use of P & K fertilizer in farm can disturb the balance of the nutrients available to crops and pollute terrestrial and aquatic ecosystems (Erich et al., 2002).

Geospatial techniques for assessment of spatial variability of soil nutrients are latest digital soil mapping technology for nutrient management in precision agriculture and enhancing global food security (Dinesh et al., 2022; Khan et al., 2014; Reza et al., 2019; Su et al., 2018; Vasu et al., 2017). Thematic mapping of soil P and K fractions using geospatial technique is an advanced level mapping of nutrient fractions rather than simply mapping of plant available nutrient form, indicating the potential capacity or reserve of soil P and K supply to crops and having practical implication on best nutrient management practices of crops. State level distribution of phosphorus fractions (Adhikari & Singh, 1994), potassium forms within soil profile (Pal & Mukhopadhyay, 1992; Singh et al., 2006) and in surface soils (Basumatary & Bordoloi, 1992; Sharma et al., 2009) was reported in India. Even field scale spatial variability of P fractions (Heilmann et al., 2005) and village level variability of K fractions (Chatterjee et al., 2015) using geostatistical tools were reported by several authors. But mapping of distribution of phosphorus and potassium fractions at farm scale using geostatistical technique has not been reported to date for precision nutrient management in India.

The objective of the present research was to evaluate the status of soil phosphorus and potassium fractions, identifying its spatial dependency through spatial modeling and mapping of its spatial distribution using geostatistical tool in geographic information system (GIS) environment at ICAR-IARI farm, New Delhi.

2. Material and methods:

2.1. Site descriptions and soil sampling

The research work was conducted at farm of the ICAR-Indian Agricultural Research Institute (IARI) in New Delhi (77°8′40.48″ - 77°10′28.07″ East longitude, 28°37′21.97″-28°38′58.74″ North latitude). The farm has a total area of about 278 hectares and is divided into various administrative blocks (Fig. 1) and several crops are cultivated during *Monsoon* and *Rabi* seasons. A total of 288 soil samples from the farm were collected using grid sampling techniques of 100 m × 100 m distance at soil depth of 0-15 cm after harvesting of *Rabi* crops, 2010-11. The collected soil samples with proper tagging were air-dried, processed and sieved with 2 mm mesh for laboratory analysis.

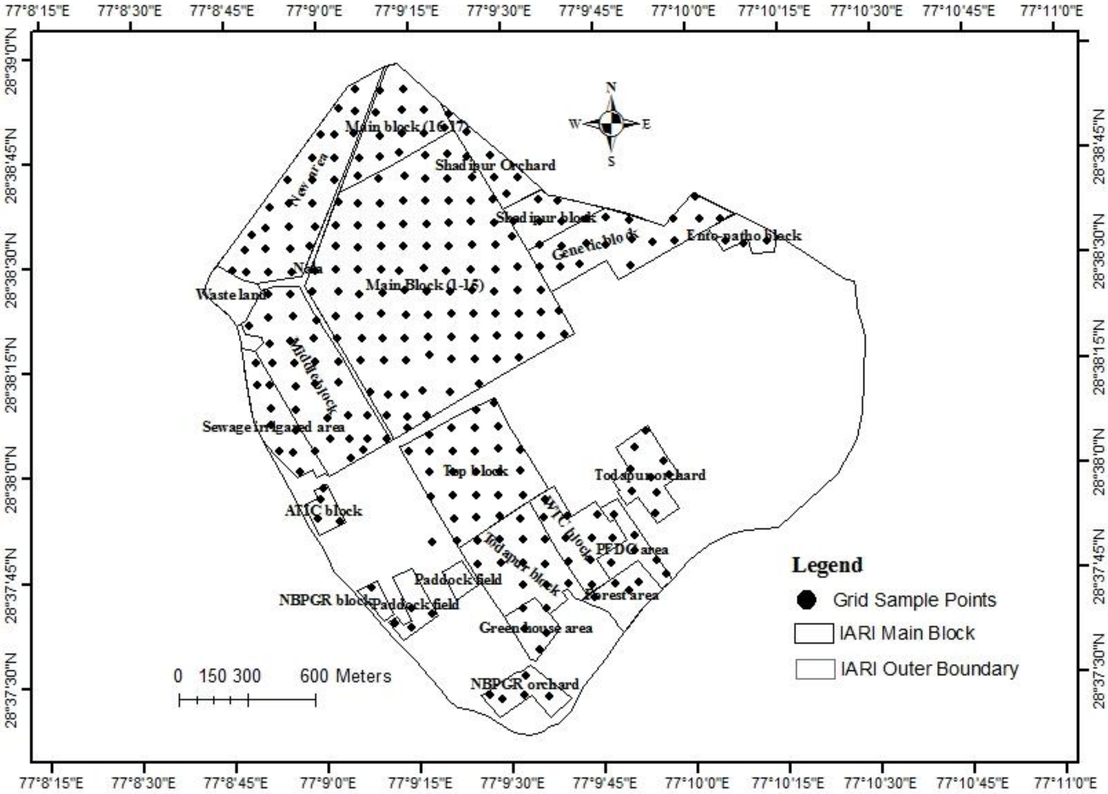


Fig 1. Location, major block and collected sample points at ICAR-IARI farm, New Delhi

2.2. Analysis of soil samples

Soil parameters such as soil pH in 1:2.5 ratio of soil & water suspension, soil organic carbon *i.e.* Walkley & Black carbon (WBC), calcium carbonate equivalent (CCE) (Piper, 1966), texture (Bouyoucos, 1962) and cation exchange capacity (CEC) (Page et al., 1982) were analyzed using standard methodologies mentioned within parenthesis. Soil phosphorus fractionation is a method for characterizing soil phosphorus availability without phosphorus speciation. Soil available phosphorus ($NaHCO_3$-P) was extracted by Olsen's extractants and phosphorus concentration in the extracted solution was measured by ascorbic acid method. The extraction procedure for several soil P-fractions involves the sequential P fractionation procedure with (i) 0.1N NaOH to extract non-occluded Al- and Fe-bound phosphorus, (ii) 1M NaCl and citrate-bicarbonate (CB) to extract P sorbed by carbonates during the previous NaOH extraction, (iii) citrate-dithionite-bicarbonate (CBD) to extract P occluded within oxides and hydrous oxides of iron (Fe), and (iv) 1N HCl to remove Ca-bound P (Page et al., 1982). These four phosphorus fractions are represented as NaOH extractable phosphorus (NaOH-P), citrate-bicarbonate extractable phosphorus (CB-P), citrate-bicarbonate-dithionite extractable phosphorus (CBD-P) and HCl extractable phosphorus (HCl-P). Estimation of CB and CBD extractable phosphorus was also followed by the standard method (Page et al., 1982). The solution P concentration was determined with reduction of phospho-molybdic acid complex by ascorbic acid reduction method (Watanabe & Olsen, 1965).

Processed soil samples were used for analysis viz. plant available K (NH_4OAc-K) extracted by shaking 5 g soil with 25 mL of 1N neutral ammonium acetate for 5 minutes (Hanway & Hiedal, 1952) and reserve K or 1N HNO_3-K by boiling 2.5 g soil with 1N HNO_3 for 10 minutes (Wood & De Turk, 1940) and the non-exchangeable K was calculated by substracting 1N NH_4OAc-K from 1N HNO_3-K.

2.3. Statistical and geo-statistical Analysis

Exploratory data analysis of soil P-& K- fractions in the farm was conducted. Trend analysis of soil attributes was conducted in Arc-GIS software. Semivariogram analysis of soil P- & K-fractions was conducted in geostatistical wizard of the GIS software. The prediction maps of soil P-& K-fractions were created using ordinary kriging interpolation technique.

3. Results and discussion

3.1. Descriptive statistics of P- and K- fractions

Descriptive statistical parameters of soil P- and K- fractions were provided in Table 1. The soil available P content ($NaHCO_3$-P) was high with mean value of 22.4 mg kg^{-1}. The soil P-fractions at IARI farm followed the sequence HCl-P (214.7 mg kg^{-1}) > CB-P (40.8 mg kg^{-1}) > NaOH-P (32.8 mg kg^{-1}) > CBD-P (31.4 mg kg^{-1}) on average data basis. It indicated that indiscriminate use of phosphorus and potassium fertilizer in the intensively cultivated farm accelerated P fixation, subsequently leading to P fertility build-up. Crops can easily absorb the available soil phosphorus from soil solution phase (intensity factor) and it could be replenished by their quantity factors (Mengel & Kirkby, 1987). Quantity factors of soil phosphorus indicate total quantity of phosphorus in soils and here, inorganic phosphorus such as Ca-bound P, non-occluded Al- & Fe-P and occluded P were major constituents of the quantity factor. Soil available K content in the farm was high with average of 157.1 mg kg^{-1}. The non-exchangeable-K content of maximum soil samples in the farm were also grouped into high class (600-1200 mg kg^{-1}) with mean value of 1077 mg kg^{-1}. Hence, quantity factor of K *i.e.* non-exchangeable-K could also supply on long term basis to intensity factor *i.e.* plant available K form while its value decreases below threshold level over plant K uptake, K leaching on irrigation or rainfall in light textured soil.

After application of P-fertilizers in soil, it forms initial reaction products with soil components like non-crystalline or short range order minerals, crystalline Fe- and Al-oxides, free calcium carbonate and alumino-silicate minerals. NaOH extractable phosphorus *i.e.* non-occluded Al- and Fe- bound P extracts Fe- and Al- phosphates coating iron oxides or some of the phosphate sorbed specifically with non-crystalline or amorphous substances in the soil (Solis & Torrent, 1989). NaOH extractable soil P (mean 32.8 mg kg^{-1}) was higher than soil available P (mean 22.4 mg kg^{-1}) in the farm. CBD extractable-P *i.e.* occluded phosphorus within crystalline iron oxides and hydrous oxide was minimum as compared to other P fractions. Similar value of CBD-P (14.6 – 32.5 mg kg^{-1}) in surface soil was also reported by Meena & Biswas (2014) in the farm.

Table 1 Descriptive statistics of soil phosphorus and potassium fractions at ICAR-IARI farm, New Delhi

Soil attributes	Mean	Variance (σ^2)	CV * (%)	Median	Interquartile range	Min	Max
pH	7.96	0.34	7.3	8.08	0.64	5.89	9.1
WBC (g kg^{-1})	3.94	2.66	41.4	3.63	1.77	0.56	11.14
CCE (%)	0.48	0.86	193.8	0.23	0.30	0.00	7.15
Clay (%)	20.7	27.0	25.1	19.6	4.80	12.6	48.3
Silt (%)	32.0	33.6	18.1	33.5	6.20	10.3	44.1
Sand (%)	47.3	79.2	18.8	47.1	7.40	11.8	70.2
CEC [cmol (p$^+$) kg^{-1}]	12.17	7.84	23.0	11.6	7.40	7.40	27.40
NaHCO$_3$-P (mg kg^{-1})	22.4	266	72.7	17.8	15.8	1.4	113.6
NaOH-P (mg kg^{-1})	32.8	600	74.7	27.4	19.2	0.7	220.8
CB-P (mg kg^{-1})	40.8	313	43.4	36.7	17.8	12.4	119.3
CBD-P (mg kg^{-1})	31.4	72.3	27.1	30.5	12.4	14.9	65.8
HCl-P (mg kg^{-1})	214.7	4186	30.1	221.4	86.4	67.3	385.4
NH$_4$OAc-K (mg kg^{-1})	157.1	7815	56.3	138.7	78.8	43.9	839.3
Non-exch. K (mg kg^{-1})	1077	20164	13.2	1050	180	820	1921

* CV- Coefficient of variation

CB-P represents labile pedogenic Ca-rich phosphorus *i.e.* it consists of mainly adsorbed P and highly soluble P (Ruiz et al., 1997). After extraction of NaOH-P in sequential P extraction method, CB-P extracts the sorbed P by carbonates during the preceding NaOH extraction. Positive and significant correlation between CB-P and calcium carbonate equivalent indicated that CaCO$_3$ content in sample interfered in the first step of phosphorus extraction and subsequently higher value of CB-P than NaOH-P. Citrate can also extract slightly soluble form of phosphorus *i.e.* dicalcium phosphate. HCl-P or Ca-bound soil phosphorus fraction was observed as highest phosphorus fractions in the farm. Similar range of HCl-P was also reported in the farm by Chatterjee et al. (2014). In the sequential fractionation scheme, HCl-P may include apatite, octacalcium phosphate and phosphorus occluded in particles of CaCO$_3$. On long term continuous application of P-fertilizer in alkaline soil, monocalcium phosphate and dicalcium phosphate was slowly converted to tricalcium phosphate, octacalcium phosphate and apatite. 0.5M NaHCO$_3$ extracts the plant available fractions of phosphorus in neutral, alkaline and calcareous soil through solubility product principle and solubility of iron and aluminium phosphate due to increase in soil pH. The available phosphorus represents a portion of Ca-P, Al-P and Fe-P.

As per guideline for classes of spatial data variability (Warrick, 1998), CB-P, CBD-P and HCl-P showed moderate data variability class (coefficient of variation *i.e.* CV 15-50 %) while $NaHCO_3$-P & NaOH-P had high data variability with CV values of 72.7% & 74.7% respectively. The plant available soil K had high data variability (CV 56.3 %) & soil non-exchangeable potassium had low data variability with CV value of 13.2%. The presence of data variability of P-&K-fractions in the farm were important for categorization into different classes in spatial distribution map for good management practices.

Data distribution of CBD-P and HCl-P had small coefficient of skewness (γ_1 = 0.60 and -0.13 respectively) with relatively small coefficient of kurtosis (γ_2 = 0.44 and -0.40 respectively) while $NaHCO_3$-P, NaOH-P, CB-P, NH_4OAc-K and non-exchangeable K had both high values of skewness and kurtosis (Table 2). All raw data did not pass the K–S test for normality (p = 0.05) *i.e.* these datasets were non-normally distributed. The median values are smaller than means of positively skewed datasets and higher than mean of negatively skewed dataset of HCl-P. The presence of a few extreme values in $NaHCO_3$-P, NaOH-P, CB-P, CBD-P, NH_4OAc-K and non-exchangeable K datasets as observed during exploratory data analysis whereby histogram increases the skewness values. In case of skewed dataset, a few large data values influence the kriging estimators but normality is not mandatory requirement for kriging. Besides, the lognormal transformation of the P-& K-fractions reduced the skewness and kurtosis value and hence, ordinary kriging after lognormal transformation of attribute values were tested for spatial interpolation.

Table 2 Coefficient of skewness (γ_1) and kurtosis (γ_2) for soil P & K fractions

Soil attributes	Skewness		Kurtosis	
	Original attribute	Ln(attribute)	Original attribute	Ln(attribute)
$NaHCO_3$-P	2.43	-0.09	8.56	0.78
NaOH-P	3.59	-0.78	19.93	4.90
CB-P	1.75	0.25	4.36	0.52
CBD-P	0.60	-0.07	0.44	-0.46
HCl-P	-0.13	-0.88	-0.40	0.26
NH_4OAc-K	2.43	0.20	12.35	0.09
Non-exch. K	1.32	0.68	4.44	1.34

Correlation matrix of P and K fractions with soil properties is provided in **Table 3**. NaOH-P was significantly and negatively correlated with soil pH (r = -0.39) and calcium carbonate equivalent (r = -0.16) at 1% level of significance. CB-P was positively and significantly correlated with calcium carbonate equivalent (CCE) (r = 0.64). HCl-P was positively and significantly correlated with CCE (r = 0.29), soil pH (r = 0.26) and clay (r = 0.24) at 1% level of significance. Available phosphorus *i.e.* $NaHCO_3$ extractable - P was negatively correlated with sopositively and significantly correlated with NaOH-P (r = 0.87), WBC (r = 0.44), CB-P (r = 0.44), CBD-P (r = 0.18) & HCl-P (r = 0.16). Hence, correlation of soil available phosphorus form and other P fractions indicated that soil P availability could be influenced by non-occluded Fe- & Al-P, CB-P fraction, occluded Fe-P, Ca-bound P and soil organic carbon content through chemical transformation and chemical equilibrium.

Non-exchangeable K is positively and significantly correlated at 1% level of significance with clay content (r = 0.48), cation exchange capacity (0.52) and WBC (r = 0.21). The results corroborate with findings of Singh et al. (2006) in soils of north east India. This may be because as soil organic matter increases, the clay-humus complex becomes more active, providing more exchangeable sites and access to the potassium (Basumatary & Bordoloi, 1992). Soil available K was controlled by clay content, WBC, CEC and non-exchangeable-K as shown by its significant and positive correlation.

Table 3 Linear correlation coefficients between soil properties at ICAR-IARI farm, New Delhi

	Soil pH	WBC	CCE	Clay	Silt	Sand	CEC	NaHCO$_3$-P	NaOH-P	CB-P	CBD-P	HCl-P	NH$_4$OAc-K	Non-exch. K
Soil pH	1													
WBC	-0.29**	1												
CCE	0.13*	-0.02	1											
Clay	0.01	0.39**	-0.04	1										
Silt	0.12*	0.15*	-0.14*	0.30**	1									
Sand	-0.09	-0.33**	0.11	-0.78**	-0.83**	1								
CEC	-0.14*	0.47**	0.02	0.73**	0.07	-0.47**	1							
NaHCO$_3$-P	-0.36**	0.44**	-0.15*	0.08	0.06	-0.09	0.19**	1						
NaOH-P	-0.39**	0.28**	-0.16**	-0.01	0.02	-0.01	0.13*	0.87**	1					
CB-P	-0.08	0.21**	0.64**	0.03	-0.05	0.02	0.14*	0.44**	0.43**	1				
CBD-P	-0.09	0.07	-0.12*	0.03	-0.29**	0.17**	0.20*	0.18**	0.27**	0.02	1			
HCl-P	0.26**	0.35**	0.29**	0.24**	0.39**	-0.39**	0.08	0.16**	-0.03	0.37**	-0.25**	1		
NH$_4$OAc-K	-0.11	0.59**	-0.09	0.29**	0.15*	-0.27**	0.17**	0.32**	0.15**	0.08	-0.04	0.38**	1	
Non-exch. K	-0.05	0.21**	-0.01	0.48**	0.02	-0.30**	0.52**	0.01	-0.03	-0.02	0.08	-0.06	0.12*	1

** and *. Correlation is significant at the 0.01 and 0.05 level (2-tailed) respectively.

3.2. Surface trend analysis

The spatial data of soil P & K fractions were analysed for identification of surface trend. There was global trend observed for CBD-P & HCl-P fractions (Fig 2). CBD-P value increased from West to East direction and North to South direction. The northern and north western side of the farm had lower CBD-P values and eastern and south eastern side of the farm had higher values. The trend of CBD-P fraction was fitted with first order polynomial and this trend was removed before geostatistical analysis. Values of HCl-P fraction decreased from West to East direction and North to South direction. The northern and north western side of the farm had high values of HCl-P fractions and the southern and south eastern side of the farm had low values. The trend of HCl-P fraction was fitted with first order polynomial and this trend was removed before geostatistical analysis.

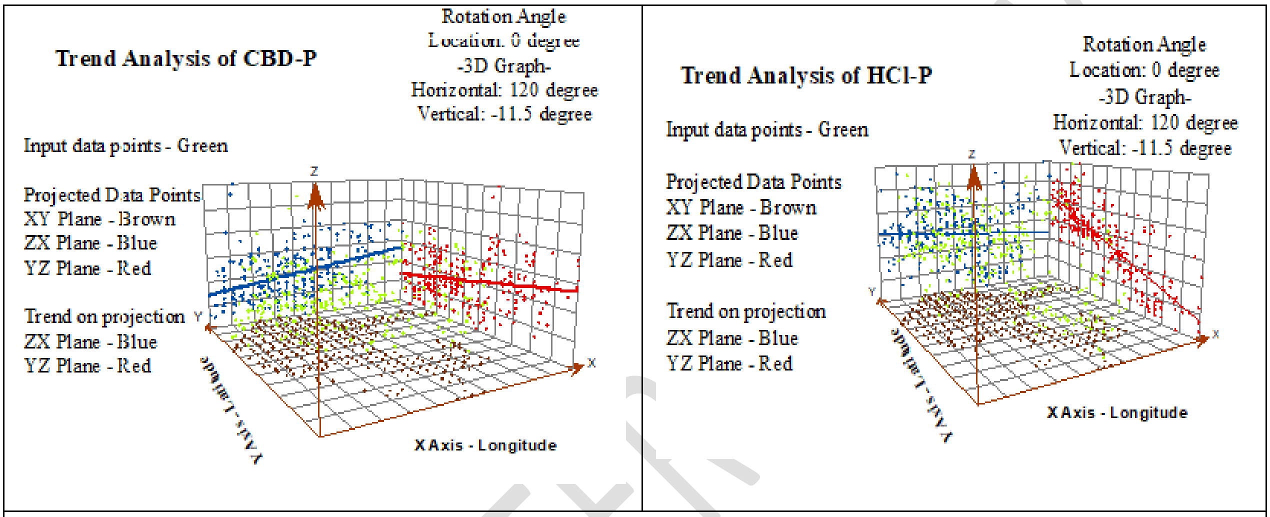
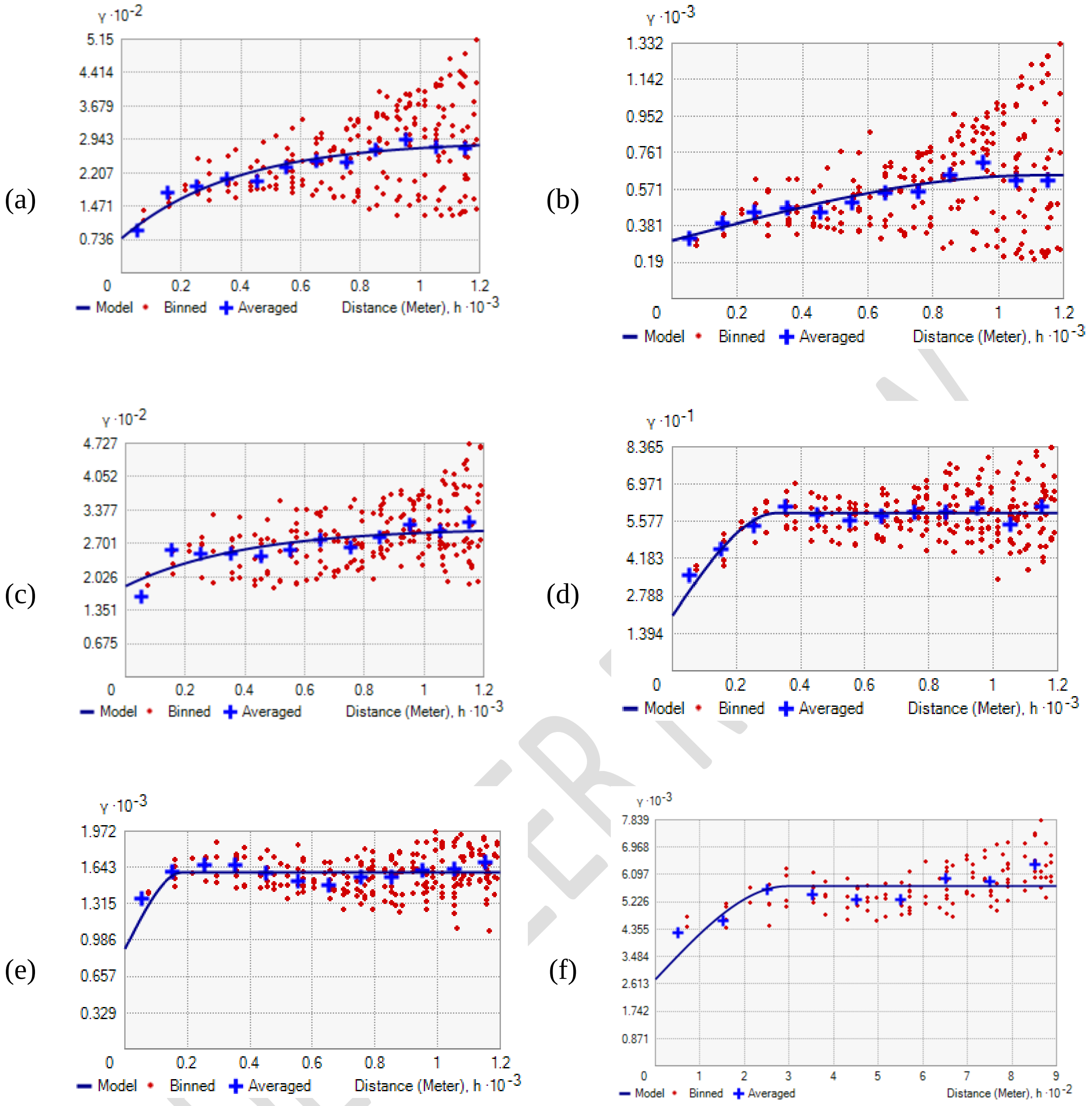


Fig 2. Trend analysis of (a) CBD-P (left) and (b) HCl-P fractions (right) at ICAR-IARI farm, New Delhi

3.3. Semivariogram analysis and spatial structure

The semi-variograms of soil P-fractions viz. $NaHCO_3$-P, NaOH-P, CB-P, CBD-P and HCl-P content and K-fractions viz soil available K and non-exchangeable K content are shown in Fig. 3. In the semivariogram, binned semivariance, average semivariance to particular lag class and best fitted semivariogram model for soil P-& K-fractions were shown in the corresponding graph. Key parameters of the best fit semi-variogram *i.e.* nugget, sill and parameter range are given in Table 4. The largest point pair distance in the present study was 2909 m and as thumb rule, active lag distance (*i.e.* lag size multiplied by no of lag size) varied from 1/3 to 1/2 (900-1500 m) of the longest point pair distance. The best fitted semivariogram model among spherical, exponential, gaussian, linear and linear-to-plateau models was selected from least residual sum of square value (RSS). In this study, the optimal semivariogram model of $NaHCO_3$-P & CB-P content was exponential, whereas NaOH-P, NH_4OAc-K, non-exchangeable-K were best fitted to spherical models. After trend removal, the semi-variogram of CBD-P and HCl-P fractions were also best fitted in spherical model. The selection of best fitted semivariogram had influence on the prediction of soil P- & K-fractions at unsampled location, particularly when the curve significantly differed in shape near the origin.



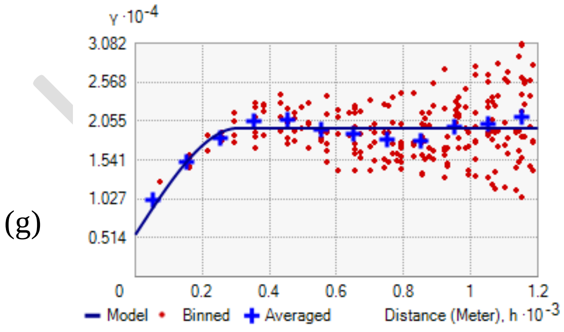


Fig 3 Experimental semivariogram and fitted models for P & K-fractions (a) $NaHCO_3$-P content, (b) NaOH-P, (c) CB-P, (d) CBD-P, (e) HCl-P), (f) NH_4OAc-K content, (g) Non-exchangeable-K at ICAR-IARI farm, New Delhi

Table 4 Parameters for best fitted semivariogram model of soil attributes in the research farm

Soil attributes	Best fitted model	Nugget (C_0)	Partial sill (C)	Sill (C_0+C)	Parameter range (A_0) (m)	Effective range (A) (m)	Proportion $C_0/(C_0+C)$	r^2
$NaHCO_3$-P	Exponential	76.4	214.2	290.6	380	1140	0.26	0.90
NaOH-P	Spherical	303.0	341.9	644.9	1123	1123	0.47	0.89
CB-P	Exponential	183.9	117.5	302.4	400	1200	0.61	0.69
CBD-P (Trend removed)	Spherical	20.6	38.4	59.0	327	327	0.35	0.75
HCl-P (Trend removed)	Spherical	905.8	692.3	1598.1	184	184	0.57	0.82
NH_4OAc-K	Spherical	2757	2970	5727	295	295	0.48	0.71
Non-Exch. K	Spherical	5565	14067	19632	308	308	0.28	0.89

The spatial 'range' of the semi-variogram for a soil attributes was the distance (h) at which semi-variance reached a plateau (sill). Parameter range and major or effective range are similar for spherical model. For exponential model, major range or effective range (A) = 3 x parameter range (A_0), which is the distance at which the sill is within 5% of the asymptote. The spatial range (effective range) of NaOH-P, CBD-P and HCl-P were 1123 m, 327 m and 184 m respectively and that for $NaHCO_3$-P & CB-P were 1140 m & 1200 m respectively. The spatial range of soil available - K & non-exchangeable-K were 295 m & 308 m respectively. Similar type of spatial range of soil available K and non-exchangeable K were reported in spatial variability mapping at village level, West Bengal (Chatterjee et al., 2015). The spatial range of the soil attribute was also the diameter of the circle of influence, representing the average maximum distance over which the property of two soil samples was spatially auto-correlated. The degree of similarity for the measured soil property of two samples increases with decreasing separation distance between the two points within its spatial range. Thus, the range provided an estimate of areas of similarity or spatial dependence.

All properties of soil P- & K-fractions showed positive nuggets (Table 4). This can be explained by short-range variability, sampling error, random error and inherent variability in soil chemical composition. The relative ratio of nugget & sill values can be used to describe the degree of the spatial structure and the ratio of < 0.25, 0.25-0.75 and > 0.75 indicates strong, moderate and weak level of spatial autocorrelation, respectively (Warrick, 1998). The range of nugget/sill ratio (*i.e.* 0.26 to 0.61) indicated that both structural and random factors influenced modest level of spatial autocorrelations for soil P & K fractions. It means that both structural factors, viz. terrain, parent material, soil mineralogy, soil chemical composition (Chand & Tomar, 1993; Wang et al., 2010) and random factors viz. land use pattern or crop planting, fertilizer management practices and crop management practices (Setia & Sharma, 2007; Sihag et al., 2005) codetermined soil properties (Goovaerts, 1997).

3.4. Spatial distribution of phosphorus and potassium fractions

The spatial distribution of phosphorus fractions (Fig 4) at ICAR-IARI farm were categorized into different classes. The bulk of IARI farm had high level of plant available soil phosphorus (> 11.2 mg kg^{-1} P) (Fig 4a). The northern corner, western side, eastern fringe and patches in Todapur block and Paddock field of the farm had very high level (22.3 – 113.6 mg kg^{-1}) of soil available P. The high level of plant available soil phosphorus was accumulated in the crop field due to continuous cultivation with P-fertilization.

In case of NaOH-P *i.e.* non-occluded Al- & Fe-bound P (Fig 4b), bulk of the farm were grouped under classes of 0.7 - 25 mg kg^{-1} P and 25-50 mg kg^{-1} P. The western side of the farm under sewage irrigation had high level (50-100 mg kg^{-1}) of NaOH-P. For occluded phosphorus within crystalline iron oxides and hydroxides *i.e.* CBD-P (Fig 4d), the major area of the farm had been grouped under first three classes (upto 45.5 mg kg^{-1} P). The south and south eastern area of the farm had comparatively higher value of CBD-P, indicating presence of oxides and hydroxides of iron and aluminium. Distribution of CBD-P in the farm was related with free oxides distribution in different soil serieses as reported by (AIS & LUS, 1976). Amorphous ferri- allumino-silicate (AFAS), allophone and imogolite content were reported as higher quantity than ferrihydrite in Inceptisols of ICAR-IARI farm (D. Chatterjee et al., 2014). These amorphous or short range minerals contributed towards higher non-occluded soil phosphorus than occluded soil phosphorus.

The distribution of CB-P in the farm was depicted in Fig 4c and bulk of the farm had 25-50 mg kg^{-1} - P). The spatial distribution of HCl-P *i.e.* Ca-bound soil P fraction (Fig 4e) at the farm followed opposite pattern of CBD-P distribution. The soil at northern and north eastern fringe of IARI farm had HCl-P of 200-385.4 mg kg^{-1} and subsequently, the value declined in southern direction. The soil of southern portion contained 67.3-200 mg kg^{-1} of HCl-P. The higher HCl-P in northern portion would be due to presence of high active calcium carbonate equivalent and high phosphorus fertilization in the intensively cropping system for long term basis (Gorai, 2015). The lower HCl-P in southern portion might be due to less fertilization in orchard of Top block, Todapur block, kisan mela ground and forest area. It might be the facts that the Ca-P compounds were converted into Al-P and sesquioxide bound P with maturity of soils (Singh et al., 2003).

The spatial variability map of available K was depicted in Fig 4f. Intermediate levels of soil available K (54 – 125 mg kg-1) were found in the southern part of the farm, excluding Todapur orchards, forest area, NBPGR block & Paddock field. The north corner, fallow land and a part within the Main Block had very high levels of available K (>200-400 mg kg^{-1}). However, the rest of the farm showed high levels of available K (125-200 mg kg^{-1}). The prediction map of soil non-exchangeable - K (Fig 4g) displayed that bulk of the farm soils had high level (600-1200 mg kg^{-1}) of non-exchangeable K and a few patches within Main Blocks, WTC & PFDC area and NBPGR orchard area had very high level (>1200 mg kg^{-1}). The spatial distribution of soil available K & non-exchangeable K at the farm had similarity with distribution of particle size fractions & CEC (Gorai et al., 2015). The high and very high level of non-exchangeable potassium in the farm was attributed by the presence of mica as dominant clay mineral with associated minerals of kaolinite, vermiculite or chlorite and interstratified minerals (Mohanty, 1997). The highest content of mica in soils developed on alluvium was due to micaceous nature of alluvium in Yamuna River. Similarly, non-exchangeable K reserves in illite-rich alluvial soils were reported as highest quantity (Subba Rao et al., 1993).

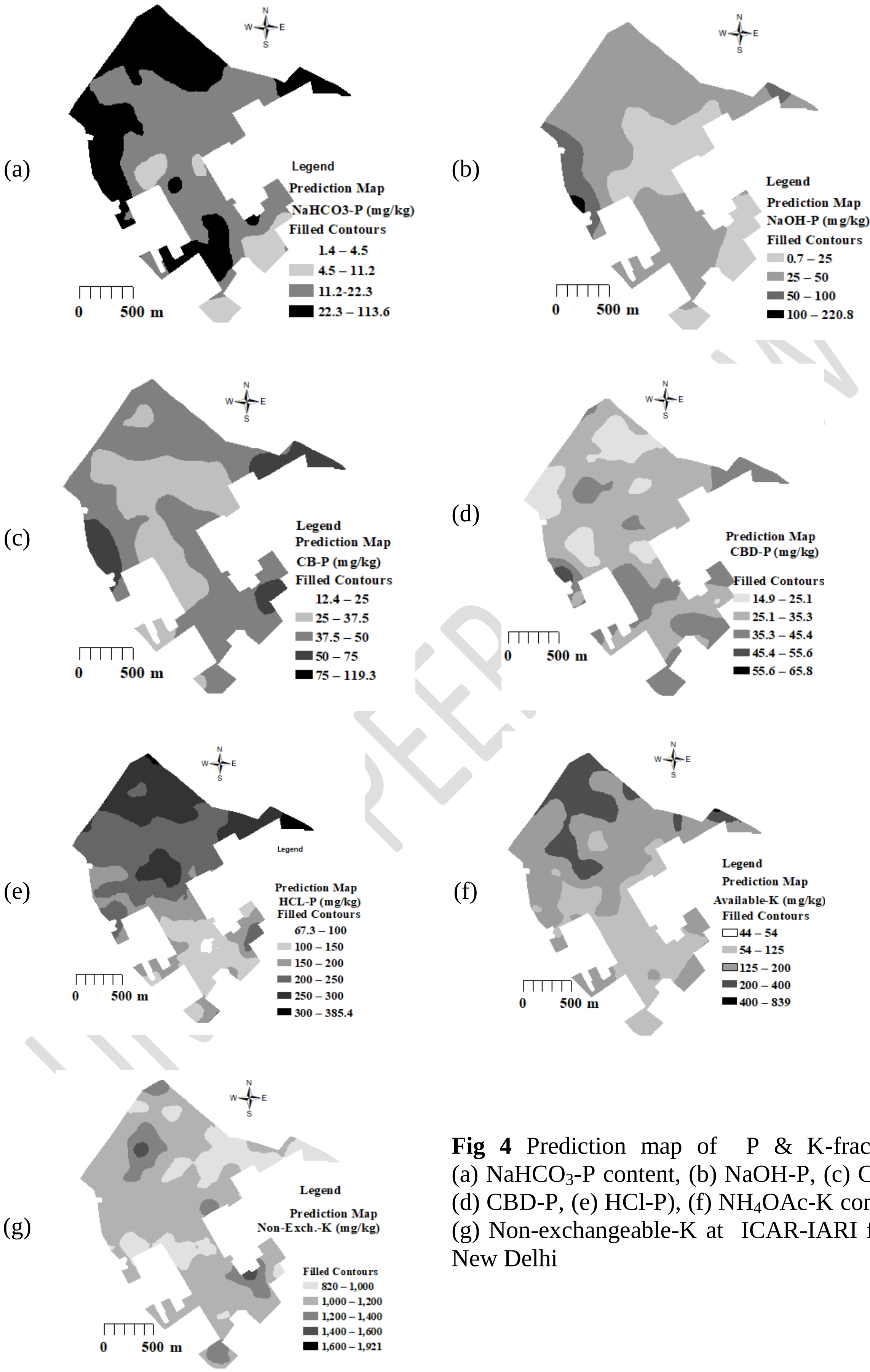


Fig 4 Prediction map of P & K-fractions (a) $NaHCO_3$-P content, (b) NaOH-P, (c) CB-P, (d) CBD-P, (e) HCl-P), (f) NH_4OAc-K content, (g) Non-exchangeable-K at ICAR-IARI farm, New Delhi

3.5. Cross validation of prediction map

The generated spatial distribution maps of soil phosphorus and potassium fractions through ordinary kriging and ordinary kriging after lognormal transformation of data were evaluated through cross validation and was provided in Table 5. Mean prediction error (MPE), root mean square error (RMSE), average standard error (ASE), mean standardized error (MSE) and root mean square standardized error (RMSSE) were used for selection of the best kriging techniques. MPE determines the degree of bias in the estimates, RMSE measures the error size and ASE is associated with standard error of prediction. Prediction model is good if MPE becomes near to zero and RMSE value is smaller & closer to ASE. In respect to MSE & RMSSE, prediction model is good if MSE becomes near to zero and RMSE value is closer to one. From analysis of cross validation error, it was observed that ordinary kriging technique was better for NaHCO$_3$-P, NaOH-P, CB-P, NH$_4$OAc-K and non-exchangeable - K than lognormal ordinary kriging. For CBD-P & HCl-P, ordinary kriging after trend removal performed better than ordinary kriging without trend removal.

Table 5 Evaluation performance of kriged map of soil properties through cross validation

Soil attributes	Interpolation techniques*	Mean prediction error	Root mean square error	Average standard error	Mean standardized Error	Root Mean square standardized error
NaHCO$_3$-P	OK	-0.1161	11.98	11.71	-0.0068	1.0213
	OK$_{LG}$	-0.2324	12.14	12.17	-0.0246	1.0509
NaOH-P	OK	-0.0051	19.10	19.45	-0.0005	0.9815
	OK$_{LG}$	0.3700	18.85	21.09	0.0274	0.8276
CB-P	OK	-0.1352	16.06	15.11	-0.0080	1.0593
	OK$_{LG}$	-0.4769	15.76	14.80	-0.02713	1.0730
CBD-P	OK	-0.0606	6.37	6.36	-0.0088	1.0013
CBD-P (Detrended)	OK	-0.0727	6.38	6.37	-0.0107	1.0003
HCl-P	OK	-0.2122	42.05	38.68	-0.0035	1.0837
HCl-P (Detrend)	OK	-0.1367	42.20	39.73	-0.0013	1.0592
NH$_4$OAc-K	OK	-1.8028	76.43	68.23	-0.0214	1.0989
	OK$_{LG}$	-2.0932	76.04	65.92	-0.0332	1.1841
Non-Exch. K	OK	-0.3144	116.40	113.72	-0.0005	1.0255
	OK$_{LG}$	-0.3679	116.18	110.90	-0.0057	1.02837

*OK – ordinary kriging, OK$_{LG}$ – Lognormal ordinary kriging,

4. Conclusion

Soil available P content at ICAR-IARI farm, New Delhi had medium to very high level. Ca - bound P-fraction was found as the major P fraction at ICAR-IARI farm, followed by non-occluded Fe- & Al- bound P and occluded Fe- P. Soil available K in the farm had medium to very high level and non-exchangeable – K content was high to very high level. Available phosphorus was positively and significantly correlated with all P fractions and soil organic carbon content. Thematic mapping of soil P and K fractions indicated both plant available form and reserve or potential capacity of soil P and K nutrients. Variable nutrient management for crops as per spatial variability of available and reserve nutrient form can enhance crop productivity, national food security and improve soil health in precision agriculture. Effective spatial range of soil P fractions viz $NaHCO_3$-P, NaOH-P, CB-P, CBD-P and HCl-P were 1140 m, 1123 m, 1200 m, 327 m and 184 m respectively; for soil available K and non-exchangeable K were 295 m and 308 m respectively, and showed moderate spatial dependency. The estimated effective spatial range indicated that 100 m of grid sampling distance is effective for generation of thematic nutrient map and subsequently precision nutrient management. The distribution of HCl-P at the farm followed opposite pattern of CBD-P distribution, indicating variation of inherent soil constituents viz. free carbonates, oxides and amorphous materials. High and very high level of non-exchangeable K reserves at the farm was contributed by presence of predominant micaceous clay mineral in alluvial soils.

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