

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 (NaHCO₃-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 descended 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 than 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. Plants absorb phosphorus and potassium nutrients from soil solution phase that is replenished by their quantity factors (Mengel & Kirkby, 1987). The distribution and forms of soil phosphorus provide key information for assessing P availability and degree of chemical weathering of soils (Sarkar et al., 2014; Singh et al., 2003). Soil phosphorus fractionation is an alternative method for characterizing soil phosphorus availability without phosphorus speciation. Consequently, inorganic P fractionation is a useful criterion to characterize the fate of P sources along with its potential availability and mobility in different soil types (Mostashari et al., 2008).

Indiscriminate use of phosphorus and potassium fertilizer in intensively cultivated farm accelerated P and K fixation, subsequently leading to P and K fertility build-up. Residual phosphorus in soil can unbalance the nutrients available to crops and pollute terrestrial and aquatic ecosystems (Erich et al., 2002). 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

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(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 is scarcely reported till date for precision nutrient management in India.

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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. Total 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.

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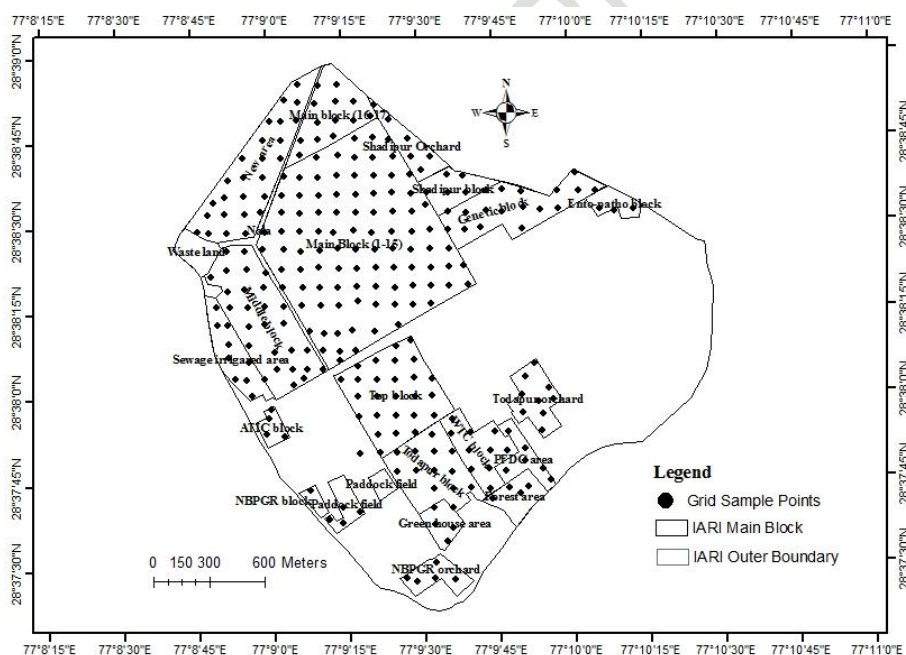


Fig 1. Location, major block and collected sample points at ICAR-IARI farm, New Delhi

2.2.

Soil pH, soil organic carbon *i.e.* Walkley & Black carbon (WBC), calcium carbonate equivalent (CCE), texture and cation exchange capacity (CEC) were analyzed using standard methodologies. Soil available phosphorus (NaHCO₃-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 ($\text{NH}_4\text{OAc-K}$) 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 $\text{HNO}_3\text{-K}$ 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 subtracting 1N $\text{NH}_4\text{OAc-K}$ from 1N $\text{HNO}_3\text{-K}$.

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 ($\text{NaHCO}_3\text{-P}$) was high with mean value of 22.4 mg kg^{-1} and ranged between 1.4 and 113.6 mg kg^{-1} . The soil P-fractions at IARI farm followed the sequence $\text{HCl-P} (214.7 \text{ mg kg}^{-1}) > \text{CB-P} (40.8 \text{ mg kg}^{-1}) > \text{NaOH-P} (32.8 \text{ mg kg}^{-1}) > \text{CBD-P} (31.4 \text{ mg kg}^{-1})$ on average data basis. The NaOH-P ranged from 0.7 to 220.8 mg kg^{-1} with standard deviation (SD) of 24.5 . The CBD-P varied from 14.9 to 65.8 mg kg^{-1} with SD of 8.5 . HCl-P was limited between 67.3 and 385.4 mg kg^{-1} . Soil available K content was high, averaging 157.1 mg kg^{-1} and ranged from 44.0 to 839.3 mg kg^{-1} . The non-exchangeable-K content of maximum soil samples in the farm were grouped into high class ($600\text{-}1200 \text{ mg kg}^{-1}$) with mean value of 1077 mg kg^{-1} and statistical range was from 820 to 1921 mg kg^{-1} .

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 aluminosilicate 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 ($14.6 - 32.5 \text{ mg kg}^{-1}$) in surface soil was also reported by other author (Meena & Biswas, 2014) in the farm.

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Comment [U7]: Unnecessary. Just say Meena and Biswas (2014)

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 [$\text{cmol (p}^+) \text{ kg}^{-1}$] | 12.17 | 7.84 | 23.0 | 11.6 | 7.40 | 7.40 | 27.40 |
| $\text{NaHCO}_3\text{-P (mg kg}^{-1}\text{)}$ | 22.4 | 266 | 72.7 | 17.8 | 15.8 | 1.4 | 113.6 |
| $\text{NaOH-P (mg kg}^{-1}\text{)}$ | 32.8 | 600 | 74.7 | 27.4 | 19.2 | 0.7 | 220.8 |
| $\text{CB-P (mg kg}^{-1}\text{)}$ | 40.8 | 313 | 43.4 | 36.7 | 17.8 | 12.4 | 119.3 |
| $\text{CBD-P (mg kg}^{-1}\text{)}$ | 31.4 | 72.3 | 27.1 | 30.5 | 12.4 | 14.9 | 65.8 |
| $\text{HCl-P (mg kg}^{-1}\text{)}$ | 214.7 | 4186 | 30.1 | 221.4 | 86.4 | 67.3 | 385.4 |
| $\text{NH}_4\text{OAc-K (mg kg}^{-1}\text{)}$ | 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 other author (D. 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 $\text{NaHCO}_3\text{-P}$ & 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 ($\gamma_1 = 0.60$ and -0.13 respectively) with relatively small coefficient of kurtosis ($\gamma_2 = 0.44$ and -0.40 respectively) while $\text{NaHCO}_3\text{-P}$, NaOH-P , CB-P , $\text{NH}_4\text{OAc-K}$ and non-exchangeable K had

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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 NaHCO₃-P, NaOH-P, CB-P, CBD-P, NH₄OAc-K and non-exchangeable K datasets as observed during exploratory data analysis with 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.

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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 ₄ OAc-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 ($r = 0.29$) and soil pH ($r = 0.26$) at 1% level of significance. Available phosphorus *i.e.* NaHCO₃ extractable - P was positively 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, available phosphorus includes a portion of non-occluded Fe- & Al-P, CB-P fraction, occluded Fe-P, Ca-bound P and soil organic carbon content as suggested by the correlation between these fractions.

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 other authors (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.

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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

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.

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.

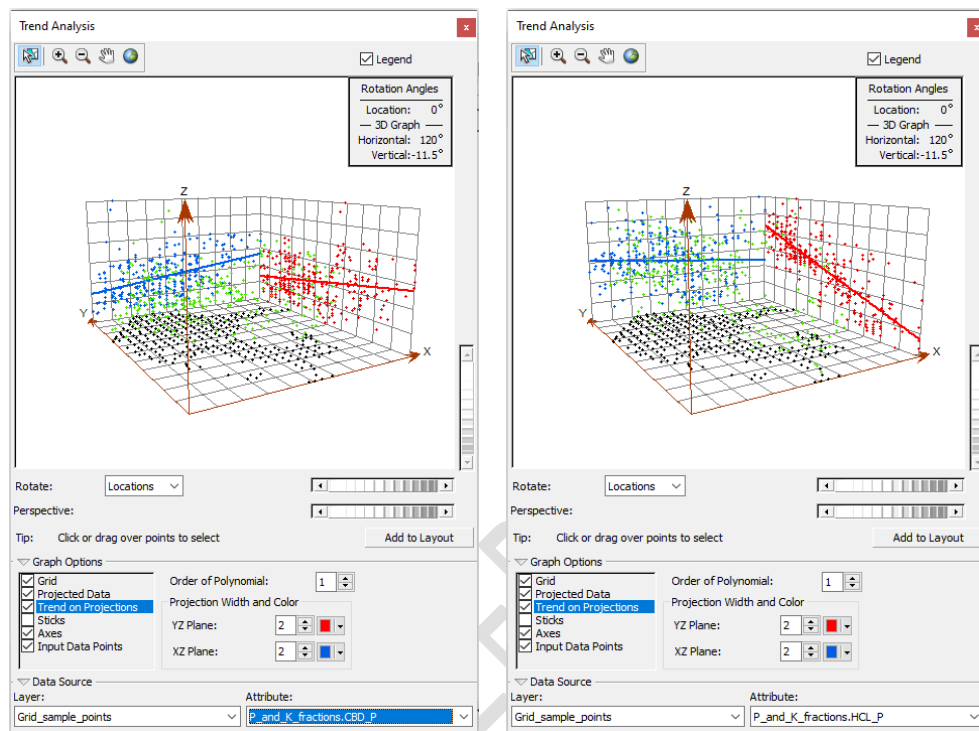


Fig 2. Trend analysis of (a) CBD-P (left) and (b) HCl-P fractions (right) at ICAR-IARI farm, New Delhi

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3.3. Semivariogram analysis and spatial structure

The semi-variograms of soil P-fractions viz. $\text{NaHCO}_3\text{-P}$, 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 $\text{NaHCO}_3\text{-P}$ & CB-P content was exponential, whereas NaOH-P , $\text{NH}_4\text{OAc-K}$, 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.

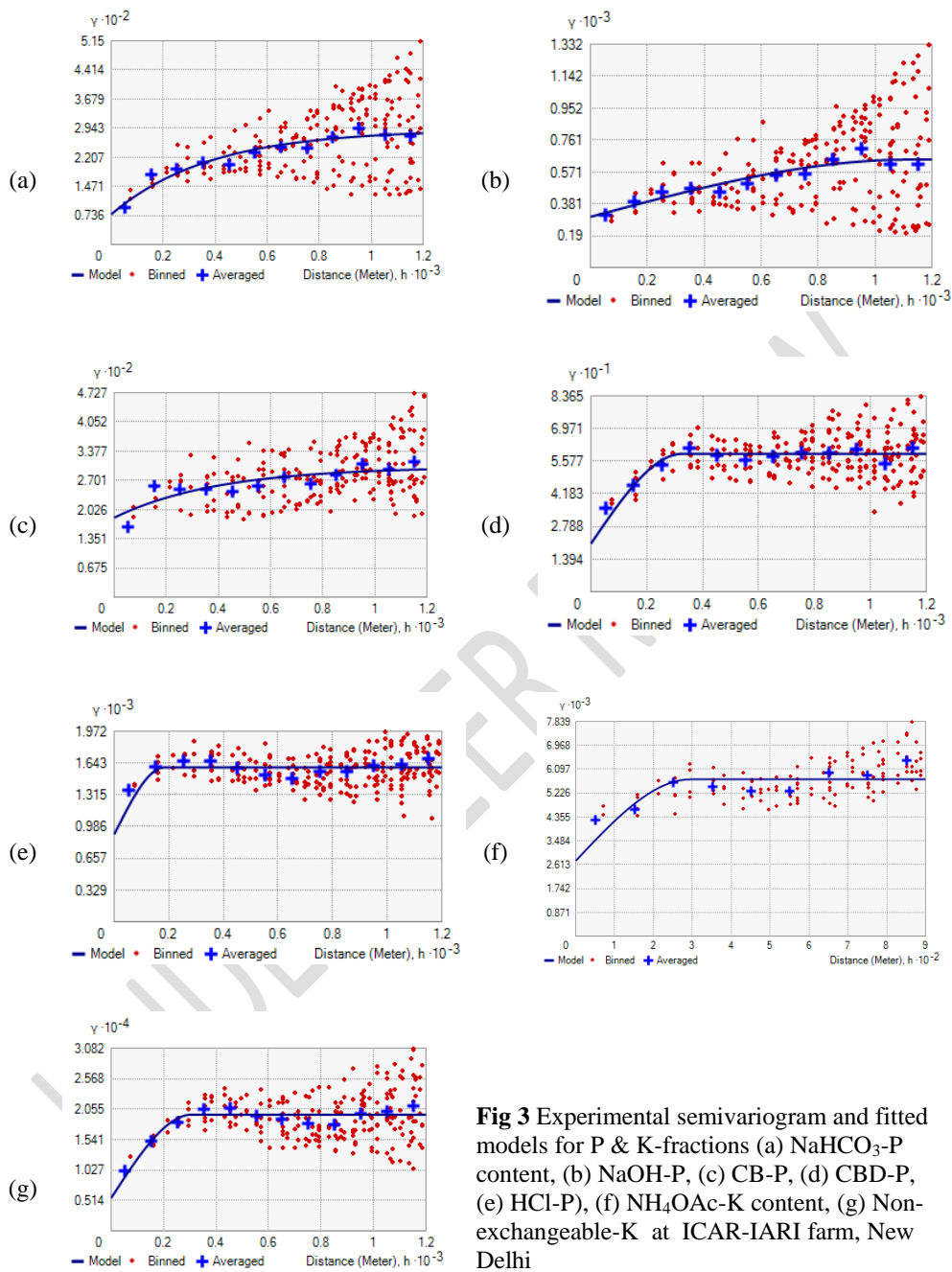


Fig 3 Experimental semivariogram and fitted models for P & K-fractions (a) $\text{NaHCO}_3\text{-P}$ content, (b) NaOH-P , (c) CB-P , (d) CBD-P , (e) HCl-P , (f) $\text{NH}_4\text{OAc-K}$ content, (g) Non-exchangeable-K at ICAR-IARI farm, New Delhi

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 ₄ OAc-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 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 (A₀), 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 NaHCO₃-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) co-determined 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 majority of the area at IARI farm had high level of plant available soil phosphorus ($> 11.2 \text{ mg kg}^{-1} \text{ P}$) (Fig 4a). The northern corner, western side, eastern fringe and patches in Todapur block and Paddock field of the farm had very high level ($22.3 - 113.6 \text{ mg kg}^{-1}$) 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.

Comment [U12]: Bulk? We use majority when referring to countable nouns.

In case of NaOH-P *i.e.* non-occluded Al- & Fe-bound P (Fig 4b), maximum area of the farm were grouped under classes of $0.7 - 25 \text{ mg kg}^{-1} \text{ P}$ and $25-50 \text{ mg kg}^{-1} \text{ P}$. The western side of the farm under sewage irrigation had high level ($50-100 \text{ mg kg}^{-1}$) 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 (up to $45.5 \text{ mg kg}^{-1} \text{ P}$). 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 series 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.

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The distribution of CB-P in the farm was depicted in Fig 4c and majority area of the farm had $25-50 \text{ mg kg}^{-1} - \text{P}$. 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 $200-385.4 \text{ mg kg}^{-1}$ and subsequently, the value declined in southern direction. The soil of southern portion contained $67.3-200 \text{ mg kg}^{-1}$ 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).

Comment [U14]: As above.

The spatial variability map of available K was depicted in Fig 4f. Intermediate levels of soil available K ($54 - 125 \text{ mg kg}^{-1}$) 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 ($>200-400 \text{ mg kg}^{-1}$). However, the rest of the farm showed high levels of available K ($125-200 \text{ mg kg}^{-1}$). The prediction map of soil non-exchangeable - K (Fig 4g) displayed that the major area of the farm soils had high level ($600-1200 \text{ mg kg}^{-1}$) of non-exchangeable K and a few patches within Main Blocks, WTC & PFDC area and NBPGR orchard area had very high level ($>1200 \text{ mg kg}^{-1}$). 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).

Comment [U15]: As above

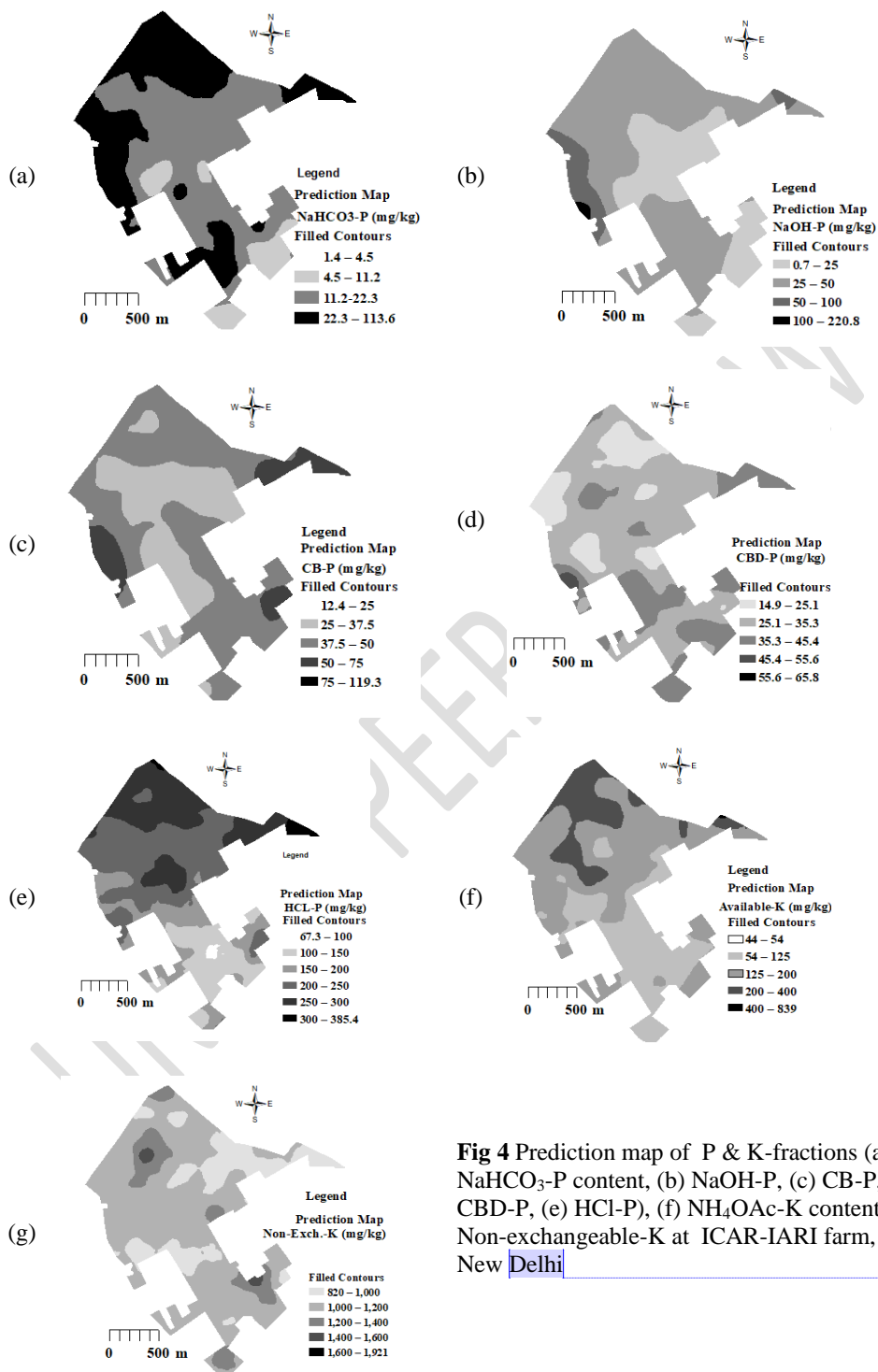


Fig 4 Prediction map of P & K-fractions (a) $\text{NaHCO}_3\text{-P}$ content, (b) NaOH-P , (c) CB-P , (d) CBD-P , (e) HCl-P , (f) $\text{NH}_4\text{OAc-K}$ content, (g) Non-exchangeable-K at ICAR-IARI farm, New Delhi

Comment [U16]: Try using colour to these map rather than grayscale. They will improve clarity.

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 NaHCO₃-P, NaOH-P, CB-P, NH₄OAc-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 at ICAR-IARI farm, New Delhi had medium to very high level (4.5 to 113.6 mg kg⁻¹). 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 (54 to 400 mg kg⁻¹) and non-exchangeable – K content was high to very high level (820-1921 mg kg⁻¹). Available phosphorus was positively and significantly correlated with all P fractions and soil organic carbon content. Effective

spatial range of soil P fractions viz $\text{NaHCO}_3\text{-P}$, NaOH-P , CB-P , CBD-P and HCl-P were 1140 m, 1123 m, 1200 m, 327 m and 184 m respectively and showed moderate spatial dependency. The distribution of HCl-P at the farm followed opposite pattern of CBD-P distribution. Effective spatial range of soil available K and non-exchangeable K were 295 m and 308 m respectively and showed moderate spatial dependency. 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.

Comment [U17]: Can you rewrite the conclusion without repeating the figures and with a focus on the implication of the findings to users of the land?

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