Azarian J. Agric. VOL (5) ISSUE 3, 2018: 76-85

Azarian Journal of Agriculture

www.azarianjournals.ir

Azarian Journals

Research article

ISSN:2383-4420

Spatial variability of nitrogen, phosphorus, and potassium using geospatial techniques on black pepper farms

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Article Info

Accepted:
26 June 2018

Keywords:
Black pepper, extrinsic, hilly area, intrinsic, macronutrients, ordinary Kriging

ABSTRACT

Black pepper is mostly planted in Sarawak covering an area of 16,093 ha. The crop is commonly cultivated on hilly topography with poor macronutrients, thus improving farm fertility is necessary. Therefore, the objective of this study was to identify the spatial distribution of N, P, and K at two pepper farms planted in hilly topography. A total of 56 and 52 soil samples (0-20 cm) were taken from SK (Kuching) and NL (Bintulu) farms for pH, N, P and K. The results were statistically analyzed using conceivable correlation and spatial distribution using ordinary Kriging interpolation method to scrutinise the macronutrients distribution in various topography. Finding revealed, SK has exhibited greater P (0.005 g kg^{-1}), while NL possessed greater soil pH (4.95), N (1.33 g kg^{-1}), and K (0.06 g kg^{-1}). Results of coefficient of variation on parameter tested ranged 6.64% to 112.92%, classified them as least, moderate, and most variable. Geostatistical analysis showed SK was best modelled with spherical, exponential, and Gaussian while NL with linear and spherical. A strong spatial dependence was calculated on soil pH, N, and K in SK and P in NL, indicating they were controlled by intrinsic factors. While, the remaining factors in SK and NL were governed by intrinsic and extrinsic factors. Spatial pattern analysis using ordinary Kriging revealed SK lessened N, P, and K contents in steeper area, whereas NL in middle farm. Conclusively, macronutrients availability were affected by topographic, farm management and fertilization application.

INTRODUCTION

Black pepper (*Piper nigrum* L.) in family of Piperaceae is a perennial vine grown for its berries extensively used as spice and in medicine. Malaysia becomes fourth largest exporter on black pepper in the year 2016 after Vietnam, Indonesia, and Brazil with the net income RM490,173 million (Malaysian Pepper Board 2017). Sarawak is the main contributor of pepper industry in Malaysia with a total 16,093 ha active land recorded in the year 2015 (Malaysian Pepper Board 2017). This crop is cultivated on laterites soil (Oxisol) with low pH values, limited cation exchange capacity (CEC), lacked P availability, and enriched of aluminum (Al) and iron (Fe).

Availability of N, P, and K in black pepper is crucial to supply nutrient for the crop growth. However, the availability of these nutrients in the soil is limited as it is affected by the crop genetic (Kong et al. 2014), environment factors particularly soil fertility (Napoli et al. 2017), and crop management (Nouri et al. 2016). Environment factors have caused the nutrients to be leached out from soil colloid especially in areas with heavy rainfall and sandy coarse-textured soil. According to Ann (2012), about 293.08 kg ha^{-1} of N, 46.41 kg ha^{-1} of P, and 264.95 kg ha^{-1} of K were removed by black pepper at 30 months of planting in clay loam soil with pH 3.85. Similar trend of nutrient removal was reported by Srinivasan et al. (2007) with N>K. This indicated these two nutrients were crucial for the crop growth and yield enhancement. In soil system, movement of N, P, and K was governed by various factors, e.g., soil acidity. Soil pH <4.5 have greater solubility of Al which may increase acidity through hydrolysis by formation of Al hydroxy (Brady and Weil 2017). This condition may cause adsorbed H and Al to the negative charged in soil colloidal and inhibited base cation (e.g. calcium, magnesium, and K) which subjected to leaching. While soluble P was fixed by Fe, Al, and

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manganese, and become insoluble to the crops. This process was serious in acidic soil which later causes major insufficient of P (Brady and Weil 2017). The problem of acidity towards N was lessened compared to P and base cations. This is because in acidic condition, crop may continually receive N in form of ammoniacal if the area has organic matter.

In order to understand the behavior of the N, P, K, and possible problems arising at the farm area level, a better approach needs to be considered, such as the use of geospatial patterning techniques to produce effective maps of soil properties. Recent studies by Bogunovic et al. (2017) and Behera et al. (2016) revealed that spatial variation of N, P, and K was affected by parent materials, topography, type of crops, climatic, and current management practices. These factors create a high heterogeneity to the soil nutrients, especially in uneven topographic. Lima et al. (2012), has highlight effect of slope has significantly influenced the variation and has close correlation to the management of the farmers. The objectives of this study are to (1) identify the spatial distribution of N, P, and K at two different black pepper areas located in hilly topography and (2) analyze the spatial patterns of N, P, and K. Using these techniques may help to map nutrient deficiency at farm areas and can recommend suitable fertilizer application and *in-situ* management practices.

MATERIALS AND METHODS

Study area

The study area is located in Bintulu and Kuching, Sarawak, Malaysia and covers about 0.71 ha (SK 0.53 and NL 0.18 ha). These areas were characterized as humid tropical region with annual temperature 26.6 ^{o}C and average rainfall 313 mm with largest rainfall recorded in October to December (Malaysian Meteorological Department 2017). These areas represent a spatial variability of N, P, and K in active black pepper farm on steeper topography. The basic soil characteristics are shown in Table 1. The first farm area, Samarakan (SK) was opened in 2004 and is now cultivated with Indian and wild variety (Rembai) of about 1,300 vines. This area has soil pH value 4.37. Generally, about 0.69, 1.62 and 2.47 g kg^{-1} of total N, P, and K were recorded in the soil, respectively. The second farm area is known as Nanga Luap (NL) which has been operating since 2014. The area has slightly greater soil pH (4.95) with 1.33, 1.78 and 5.47 g kg^{-1} of N, P, and K, respectively. The farm is currently cultivated with the Indian and Kuching variety of approximately 200 vines.

Table 1. Basic soil physical and chemical properties

Area	pH	N	P	K	Textural
		g kg^{-1}			
SK	4.37	0.69	1.62	2.47	Sandy Loam
NL	4.95	1.33	1.78	5.47	Sandy Clay Loam

All farm areas practiced clean weeding and cultivated with least consideration on soil conservation practices such as terracing and cover crops as proposed by the Malaysian Pepper Board (Malaysian Pepper Board 2016; Tanaka et al. 2009). SK applied more NPK fertilizer at 300 g/vine compared to NL which used only 100 g/vine with the reason to induce flowering of black pepper. Among the few reasons that could explain the difference in the amount of fertilizer use are the age of crops, constrains in sourcing of fertilizer, and background experience related to black pepper production. Basically, NL has intensively applied chicken manure and burned residue as substitutes to chemical fertilizer.

Soil sampling and laboratory analysis

The soil samples were collected from September to October 2015. Soils (0 to 20 cm) were sampled using probability sampling techniques to represent the area as affected by steeper and uneven topography with 56 and 52 total samples collected from SK and NL, respectively (Figure 1). Total soil sample in each area were randomly sampled which represent the whole active black pepper areas. The sampling area was set 2 m far from the first non-living pole in each side to capture only active growing areas. Each point was subsamples for four different point (about 0.5 m around sampling point) and mixed as composite samples. Soil samples were air dried at room temperature for three days, pulverized, and sieved through 2 mm prior to analyzing for soil pH

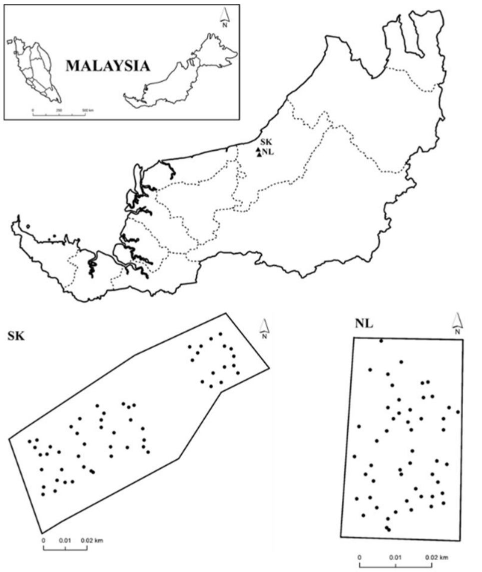


Figure 1. Study area and point of soil sampling in SK and NL

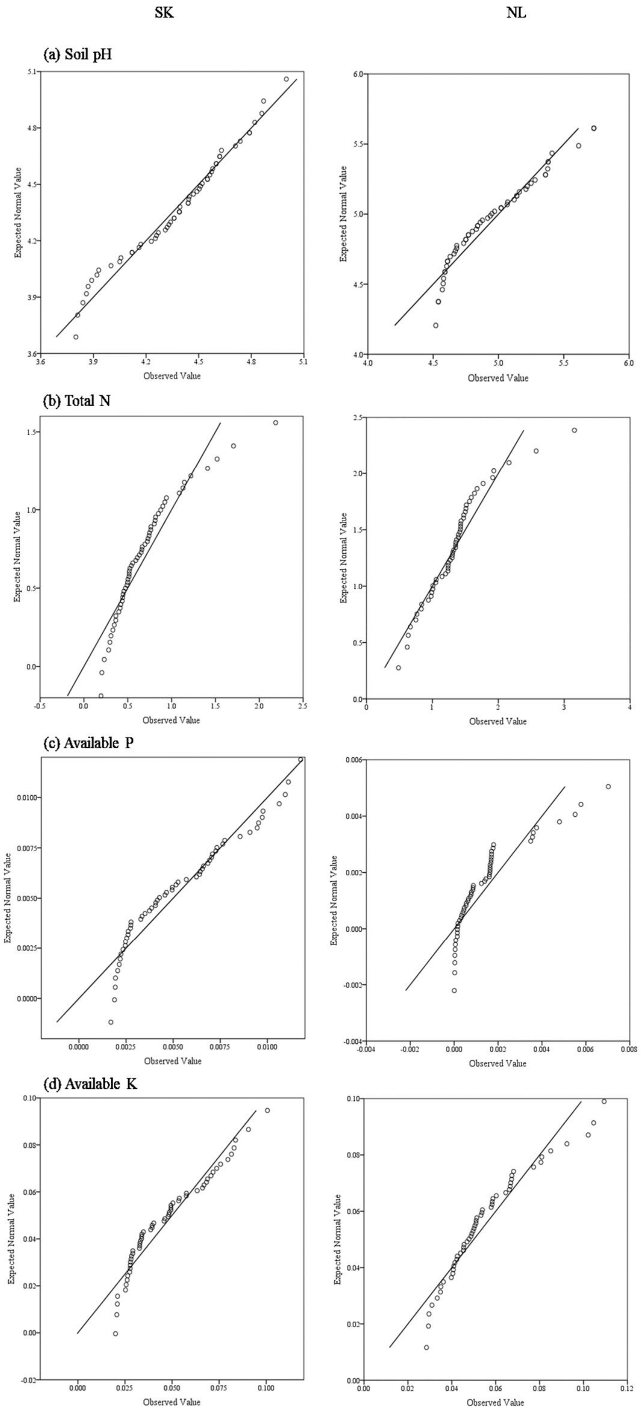


Figure 2. Normal Q-Q plots of raw data

(pH) (Tan 2011), total N (Hach et al. 1985), available P (Sarker et al. 2014; Tan 2005), and available K (Tan 2005). The total N was determined by AutoAnalyzer 3 (SEAL Analytical, Model HR), available P using UV-Vis Spectrometer at 882 nm (Lambda 25), and available K using Atomic Absorption Spectrometer (Perkin Elmer, Model AA800).

Normality of the data

Normal Q-Q plots were produced accordingly for both areas (Figure 2). A normal data distribution was displayed by soil pH in both areas (SK and NL) except a few samples slightly deviated at both ends. Right skewed data was observed for total N and available K in SK and NL. Total N in both areas were unnormalized and was confirmed by Kolmogorov-Smirnov (K-S) test which four outliers were removed in SK and two outliers in NL. A platykurtic and leptokurtic curve shape was displayed by available P in SK and NL, respectively. Four outliers from NL were removed accordingly to normalize the data.

Statistical and geostatistical analysis

The descriptive statistics were used to describe variation of the data by calculating mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis. The shape of data was observed and viewed with normal quantile-quantile plot (Q-Q) and normality was performed with Kolmogorov-Smirnov (K-S) at p=0.05. The outlier was removed temporarily to obtain near normal distribution. All the calculation was performed using JMP Statistical Discovery from SAS (Ver. 10) and IBM SPSS (Ver. 23).

Geostatistical analysis was calculated using isotropic and best fitted model was selected accordingly. Linear, spherical, exponential, and Gaussian were used to represent spatial dependence of the parameters and calculated using Geostatistics for Environmental Sciences (GS+ Ver. 10). Interpolation accuracy was performed using leave-one-out cross-validation technique as described by Liu et al. (2013) to ensure reliability of predicted modelled. The data was calculated to check the mean error (ME), absolute mean error (AME), and root mean squared error (RMSE) as follows:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Pi - Mi)$$

$$AME = \frac{1}{n}\sum_{i=1}^{n}[(Pi - Mi)]$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Mi)^2}$$

Where *n*, *Pi*, and *Mi* are the total number of samples, predicted values, and observed values of observations.

The spatial correlation on measured samples was calculated with projected semivariogram modelled. Distribution maps of the soil parameters

Table 2. Descriptive statistics of soil properties in SK and NL

Parameters	Area	Mean	SD*	CV*	Skewness	Kurtosis
pH	SK	4.37	0.30	6.86	-0.23	-0.57
	NL	4.95	0.33	6.64	0.65	-0.44
N (g kg^{-1})	SK	0.69	0.38	40.60**	0.99**	1.25**
	NL	1.33	0.47	22.96**	0.34**	1.49**
P (g kg^{-1})	SK	0.005	0.003	53.41	0.58	-0.75
	NL	0.001	0.002	112.92**	1.81**	3.08**
K (g kg^{-1})	SK	0.05	0.02	44.10	0.69	-0.52
	NL	0.06	0.02	34.98	1.08	0.91

* SD Standard deviation; CV coefficient of variation

** value after log transformation

were generated using ordinary Kriging and produced in ArcGIS (Ver. 10.5). The use of ordinary Kriging was to minimize the error variance produced by Kriging variance which provides a better spatial estimation.

RESULTS AND DISCUSSIONS

Descriptive statistics

Calculated data for mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis for soil pH, total N, available P, and K were shown in Table 2. Several outliers were removed temporary for this statistical analysis to normalize the data. In geostatistic, normalized data was important to avoid misinterpretation and prior to Kriging analysis, outliers were put back to the datasets to honor the existence (Fu et al. 2010). After log transformation, CV values on total N in SK and total N and available P in NL were reduced from 55.75 to 40.60, 35.11 to 22.96, and 113.07 to 112.92, respectively. The skewness and kurtosis were reduced significantly to a near distribution.

The soil pH in SK was revealed to be extremely acidic and in NL was strongly acidic (USDA 1998). General soil acidity in many tropical countries is mainly attributed to intensive weathering which elevated concentrations of Al and Fe (Wu et al. 2017; Wu et al. 2016). The total N in NL (1.33 g kg^{-1}) was two folds greater than SK (0.69 g kg^{-1}) which benefits from over burned residue contained in NL. While available P has exhibit SK has five folds greater than NL which may cause by different cultivation years, soil pH and texture. Accordingly, P was easily released from greater sandy fraction due to incapability to hold the ions and competing exchangeable site in acidic condition (Brady and Weil 2017; Tahir and Marschner 2017). Contrarily, lessened availability in both areas could arise from fixation of acidic cations (pH <5) which has been showed in Table 1 to have significantly greater reserve P (1.62 to 1.78 g kg^{-1}).

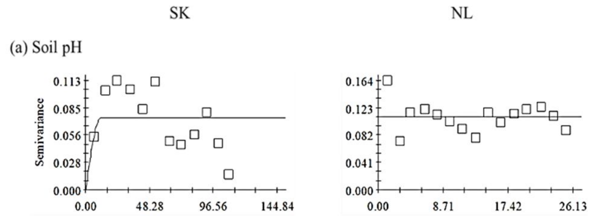
Concentration of K was comparable in both areas and was governed by soil acidity which replaced exchangeable site with Al^{3+} and H^+ and leach the ion from soil colloidal (Brady and Weil 2017; Rosolem et al. 2010). The concentration of N, P, and K in these studies was lessened compared to other researcher in tropic country. About 1 and 0.007 g kg^{-1} of N and P, respectively were reported in 20 years of oil palm plantation with a minimal soil management practices (Senjobi et al. 2013). Behera et al. (2016) has reported about 0.07 g kg^{-1} of P and 1.23 g kg^{-1} of K concentration in the tropic.

The coefficient variation (CV) was used in this study to interpreted variability. According to Zhang et al. (2007), the CV <10%, 10-90%, and >90% indicated least, moderate, and most variability, respectively. The soil pH in both areas is classified as least variable with NL having the lower CV compared to SK. Similar value of lower CV on soil pH was reported by Behera et al. (2016) and Senjobi et al. (2013). This is attributive of the deliberate adjustment of soil pH by over burned residue present in NL area (Tabi et al. 2013). The greater CV value in NL (112.92%) was comparable to finding by Behera et al. (2016) which reported about 127%. The reason contributed to this greater value could cause by heterogeneity of fertilizer application in particular area. In general, the moderate variability is governed by management and topography while high variability by farm management (Vasu et al. 2017; Kilic et al. 2012).

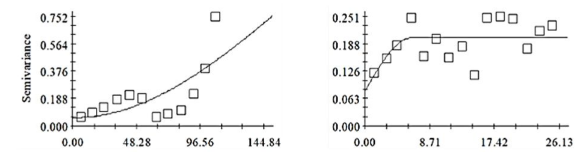
The skewness (-0.23 to 1.81) and kurtosis (-0.75 to 3.08) of soil parameters indicated nearly normal distribution with skewness near to zero and kurtosis near to three. Even though the skewness and kurtosis value for certain samples were far from initiated value, the raw data distribution was closed to normalized (Figure 2).

Geostatistical analysis and cross-validation of the model

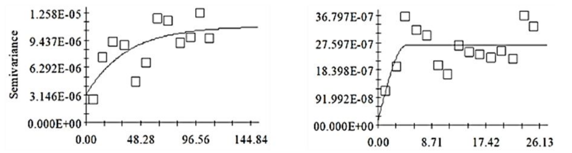
A geostatistical analysis generated for both areas on soil pH, total N, available P, and K are showed in Figure 3 and their parameters are presented in Table 3. The best-fitted model was selected based on lower residual and higher coefficient of determination (Guan et al. 2017; Yang et al. 2017). The fitted model used for SK was exponential, spherical, and Gaussian, while NL's model was linear and spherical.



(b) Total N



(c) Available P



(d) Available K

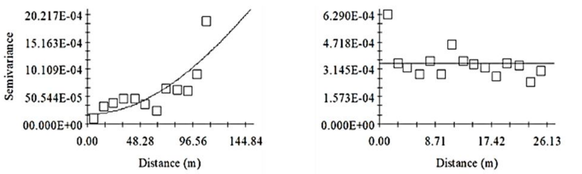


Figure 3. Calculated semivariograms of soil properties with the lines indicating best fitted model

In NL, soil pH and K were demonstrated to have no spatial structure (pure nugget effect) due to linear fitted model. This is an indication that soil properties have been randomly and independently distributed. The nugget values for soil pH in NL was relatively high in the range of 0.108. This is attributed to the inefficient capturing of spatial dependence of the data and high heterogeneity (Takoutsing et al. 2017). In spite of this, lower nugget value in most of the study areas indicated that sampling error is negligible, and the positive nugget and sill in this study were caused by sampling error and inherent variability.

The spatial correlation range on SK was N (419.33 m), P (107.70 m), and K (538.49 m). At a glance, the wider range in SK suggested influence from environmental and topographical factors (Takoutsing et al. 2017; Teng et al. 2017). However, shorter range in NL has a close relationship with anthropogenic disturbance from the farmers. The current results imply the soil properties in SK were affected by undulating topography and susceptible to variation with exposure to precipitation. In NL, disturbance of spatial correlation range was primarily caused by plantation and development of new black pepper areas.

The spatial dependence was calculated with nugget to sill ratios. According to Cambardella et al. (1994), the ratios were classified as strong (<25%), moderate (25-75%,), and weak (>75%). The soil pH and K in NL were shown to have weak spatial dependence caused by one extrinsic factor, specifically the management practices of both areas. A moderate spatial dependence was recorded in NL on N and SK on P which was indicative of the values being very dependent on soil properties which are governed by extrinsic and intrinsic factors. The remaining soil properties (P in NL and soil pH, N, and K in SK) have been identified to have strong spatial dependence which are influenced by parent material, topography, type of crops, and soil texture present at the farm area level (Guan et al. 2017; Wang et al. 2009) in a particular area. A strong spatial dependence in SK (soil pH, N, and K) were similarly reported by Behera et al. (2016) which examined a major disturbance through application of fertilizer and concurrent farmer practices to sustain their crops. Alternatively, a weak spatial dependence in NL on soil pH and K were reported by Bogunovic et al. (2014) which conclude a dominance of lower soil pH <5.0 (60%) and K <0.05 g kg^{-1} (62%) could be initial warning of this limitation in the areas.

The cross-validation on selected soil properties was calculated in order to examine the reliability and accuracy of the predicted model. Actual and predicted values were calculated with mean error (ME), absolute mean error (ASE), and root mean square error (RMSE) equations (Table 4). The ME value was in the range of -0.0061 to 0.0005, close to zero. The value range is indicative of a better model performance with unbiased interpolation prediction. Whereas measured parameters of ME particularly on soil pH, N, and K in NL and N in SK produced negative value and was shown to be underestimated than predicted value (unshown). The lower values of AME and RMSE ranging from 0.0013 to 0.3605 and 0.0016 to 0.5081, respectively indicated a good

Table 3. Theoretical fitted model on soil properties in SK and NL

Parameters	Area	Model	Nugget (C_0)	Sill (C_0 + C)	Range (m)	Spatial dependence
pH	SK	Spherical	0.0001000	0.074200	11.40	Strong
	NL	Linear	0.1086532	0.108653	25.15	Weak
N (g kg^{-1})	SK	Gaussian	0.0550000	2.220000	419.33	Strong
	NL	Spherical	0.0792000	0.202400	6.29	Moderate
P (g kg^{-1})	SK	Exponential	0.0000032	0.000011	107.70	Moderate
	NL	Spherical	0.0000002	0.000003	4.58	Strong
K (g kg^{-1})	SK	Gaussian	0.0001800	0.009620	538.49	Strong
	NL	Linear	0.0003489	0.000349	25.15	Weak

Table 4. Cross-validation of ordinary Kriging

Parameters	**Area**	**ME**	**AME**	**RMSE**
pH	SK	0.0001	0.1445	0.2032
	NL	-0.0061	0.2594	0.3233
N	SK	-0.0002	0.1611	0.2317
	NL	-0.0153	0.3605	0.5081
P	SK	0.0000	0.0013	0.0016
	NL	0.0000	0.0013	0.0017
K	SK	0.0005	0.0119	0.0155
	NL	-0.0008	0.0146	0.0193

Table 5. Pearson's correlation among soil properties in SK and NL

Area	**Parameters**	**pH**	**N**	**P**	**K**
SK	pH	1			
	N	**0.3502**	1		
	P	0.1474	**0.6156**	1	
	K	-0.1324	**0.5047**	**0.6163**	1
NL	pH	1			
	N	-0.0579	1		
	P	**0.4702**	0.1326	1	
	K	**0.4248**	0.2130	0.1963	1

* values in bold are significance p=0.05

performance of the model with an acceptable level of accuracy.

Relationships between soil properties

The correlation coefficient at p=0.05 results are shown in Table 5. Soil pH is positively correlated with N in SK and P and K in NL. Soil pH plays an important role in which increases soil pH >5 may decrease the solubility of Al and Fe, thus increases the availability of N, P, and K in particular farm areas (Raboin et al. 2016). This may evidence of lessened availability of these nutrient in soil as subjected to lower soil pH (4.37 to 4.95) reported in this study compared to adjustable soil pH ~5.35 able to provide about ~0.02 g kg^{-1} of P and ~0.27 g kg^{-1} of K (Behera et al. 2016).

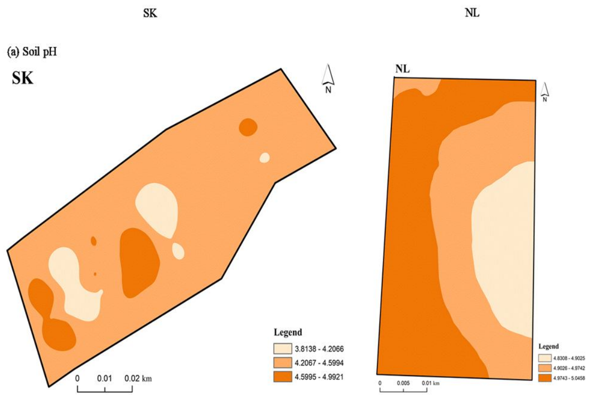
Particularly, high correlation was observed in SK on N/P (0.6156), N/K (0.5047), and P/K (0.6163). This correlation ascribed to the management of soil system whereas availability of this nutrient slightly increased. As seen in SK, improvement and correction of nutrient through fertilization scheme and supplementary of organic matter eventually increase nutrient availability and replenished nutrient retention for period of time (Goulding et al. 2008; Snapp et al. 1998). This is because the availability of nutrient was subjected to various factor for example soil pH, soil texture, topography, and recent management implies by farmers.

Spatial prediction of soil parameters

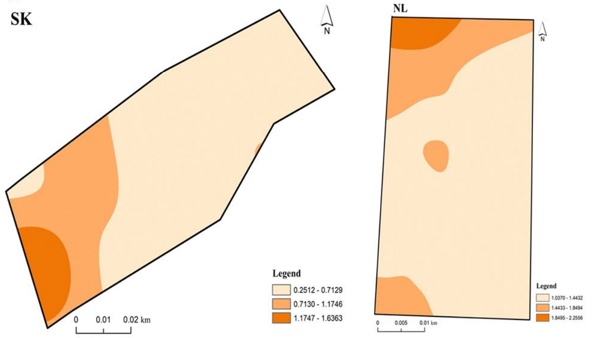
The ordinary kriging has been mapped to shows the trend of soil parameters of both areas. As shown in Figure 4, predicted values of soil pH ranging from 3.81 to 4.99 on SK and 4.83 to 5.05 for NL. Concentration of nutrient was showed NL has greater range of N (1.04 to 2.26 g kg^{-1}) and K (0.05 to 0.08 g kg^{-1}) while SK exhibit greater P with 0.002 to 0.01 g kg^{-1}.

In SK, the lowest soil pH (3.81 to 4.21) was recorded in the south west area, and in the case of NL, soils of higher acidity (4.83 to 4.90) can be found in the eastern area. Higher pH (4.90 to 5.05) soils in several areas in NL could be caused by burned residue which indirectly alleviates soil acidity (Navas et al. 2012). The availability of N, P, and K in SK was unaffected by soil pH as seen in Figure 4. Concentration of this nutrient was greater in south west and decreasing to the north east. The main reason contributed to the nutrient patterns was topography of the area in north east steeper than south west which has high potentials to caused movement and transportation of the nutrient out from active growing black pepper area (Uzoho et al. 2016; Samndi and Tijjani 2014). This was confirmed by Samndi and Tijjani (2014), steeper topography has high tendency to cause high variation of nutrient in soil system and move the nutrient to the stabilizing area, especially area with a minimal soil management (e.g. free terracing and clean soil surface).

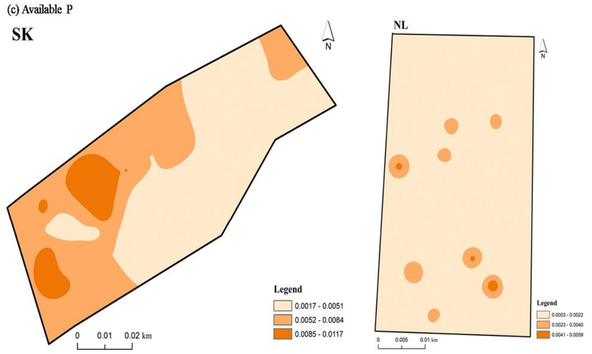
Availability of NL coincided with correlation studies presented in Table 5 which higher soil pH may have higher P and K. Referred to Figure 4,



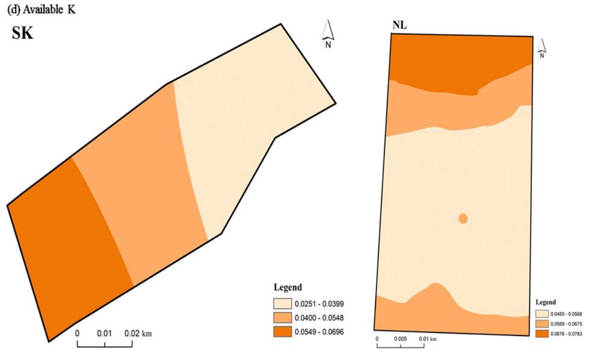
(a) Soil pH



(b) Total N



(c) Available P



(d) Available K

Figure 4. Spatial variability map of soil pH, total N, available P and K

availability of N and K were similar which greater concentration was shown in north and south area while the middle area was experiencing relatively lessened N (1.04 o 1.44 g kg^{-1}) and K (0.05 to 0.06 g kg^{-1}). About two folds lessened N and K reported between the north and south towards middle area which comparable in this study. The benefits of higher soil pH in NL have shown significantly greater availability of nutrients (e.g. N and K) compared to SK. However, availability of P was dominated by 0.0003 to 0.0022 g kg^{-1} and a few areas have greater concentration. The availability of P in this area could actively uptake by black pepper which has showed lessened in concentration values or caused by diminishing amount of fertilizer applied. According to Srinivasan et al. (2007), comparable amount of P was actively uptake by black pepper to increase internode growth, especially in younger crop.

In one particular area, availability of nutrients for black pepper uptake was approximately 0.33% and 0.08% P; and 0.73% and 1.01% for K in SK and NL, respectively. This indicated that some area in SK particularly along south west to north east are experiencing deficiencies of N and K. This behavior was evidenced by the mobility of K ions which move freely in soil system, especially on coarse texture when subjected to area topography and heavy rainfall (Sharma and Sharma 2013). Besides, younger crop age in north east area may not be able to effectively absorb nutrients due to improper root formation (Šimůnek and Hopmans 2009).

The deficiency of P may invisible due to greater availability and sufficient crop uptake from longer year of cultivation. While NL, area in middle may experiencing deficiencies of N and K due to lessened nutrient availability. A massive deficiency of N and K has been observed and reported in farm areas even though it has gentle slope compared to SK. The reason could support this occurrence was formation of three eroded drains in the middle area has caused rapid movement of N and K from soil colloidal and preventing efficient uptake (Liu et al. 2018). A similar trend of lessened nutrient reported in area with eroded soil with the reason of incapability to hold and retain the nutrient in soil system (Havlin et al. 2005).

CONCLUSIONS

In this study, the spatial distribution of N, P, and K in two black pepper farms have been revealed to be best fitted with linear, spherical, exponential and Gaussian. Area in SK has shown to be modelled with Gaussian, exponential and Gaussian on N, P, and K, respectively. While NL has performed well with spherical and linear on N, P, and K. A strong spatial dependence was reported on N and K in SK and P in NL, indicating these nutrients were governed by intrinsic factors; e.g. parent material, topography, and soil texture while moderate spatial dependence showed for P in SK and N in NL which caused by disruption of intrinsic and extrinsic factors (e.g. farmer management and fertilization). Another nutrient which is K in NL has exhibited a weak spatial dependence that shown to be influenced by management of the farmer toward their farm areas.

The spatial interpolation using ordinary Kriging has shown relationship of topography, soil texture, and farmer management (e.g. free terracing and clean soil surface) has affected the distribution of N, P, and K in both areas. SK revealed soil pH insignificantly affects distribution of N, P, and K whereas the greater concentration on higher topography (south west) and lessened in steeper area (north east). Furthermore, NL showed greater distribution of N and K in north and south area because formation of eroded drain in the middle. Therefore, proper fertilizer and farm management are required to remedy the situation in the study areas. Integrating the spatial analysis may help to give an overview of nutrient availability and improve nutrient uptake for black pepper.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Ajeng Wan and Mr. Jambai Ango for their permission to use the black pepper farms. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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