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Spatial Distribution of Soil Properties and Soil Fertility Status in the Paddy Rice Field of Oransbari

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ABSTRACT

Soil properties and soil fertility status of paddy rice fields are considered important factors related to the yield and production of rice; therefore it is essential to understand those properties across the farm. The objectives of this research is to quantify the soil properties and soil fertility status of paddy-rice soil and their spatial variability in Oransbari. Forty-two composite soil samples (0-30 cm) were taken across paddy rice fields and analyzed for soil chemical properties and fertility status. Geostatistical analysis and ordinary kriging interpolation methods were used to quantify soil variability and its fertility status across the farm. The results showed that total soil Nitrogen ranges from 0.11% to 0.17%), organic-C (1.47-6.94%), C/N ratio (11-47), total-P (13-99 mg 100 g^{-1}), available-P (30-227 mg kg^{-1}), total-K (27-54 mg 100 g^{-1}), soil pH (5.83-6.93), base saturation (70-100%), and CEC is 30.51-51.23 me 100 g^{-1}. The spatial variability of all soil characteristics exhibited medium and fit the stable model, except for available Phosphorus and Potassium. Most rice paddy fields in Oransbari showed high soil fertility status, which indicated that high-yield rice production can be achieved for this region, however, land management factors should be considered for sustainable land use.

Keywords: Geostatistics, rice field, soil fertility, spatial distribution

INTRODUCTION

South Manokwari Regency, West Papua Province is the center of agricultural commodity development areas, including lowland paddy-rice crops. Most of the paddy rice fields in this region are in the Oransbari and Ransiki Districts with a productivity of 4956 kg ha^{-1} (BPS Papua Barat, 2023). This value is relatively low in comparison to the national productivity of 5238 kg ha^{-1} in 2022. Several important factors that can cause low productivity of rice plants include the physical, chemical and biological properties of the soil. In addition, the availability of nutrients also plays a role in the level of productivity of rice fields, especially macronutrients of nitrogen, phosphorus, and potassium. The availability of these nutrients is determined by inherent factors in the form of soil parent material and dynamic factors that change, including soil processing, irrigation, and fertilization. Another factor is the low organic matter content of the soil in paddy-rice fields, which is one of the main problems causing low productivity of rice fields. Around 65% of the 7.9 million ha of paddy rice fields in Indonesia have low to very low organic matter content (organic-C <2%) (Agus and Irawan, 2004). To achieve the same level of production, this land requires higher inputs than land with an organic matter content of >3%, low total-P levels (17%) and low total-K (12%). These factors are closely related to the obstacles generally faced in rice fields, namely the problem of soil fertility and fertilization that does not follow the status of soil nutrients (Hidayanto et al., 2017; Hidayanto and Yossita, 2019). Paddy rice cultivation is a main source of nourishment for over half of the world's population. The productivity and sustainability of rice farming are significantly influenced by soil properties and fertility. Grasping the spatial distribution of these soil attributes is crucial for effective soil management, optimizing fertilizer use, and enhancing crop yields. The spatial variation of soil characteristics can vary from point to point. These differences may occur

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due to changes in land use and management practices or to natural variation. Even over short distances, these soil properties differ from point to point; within fields and across shorter distances, soil properties also vary significantly, even across locations that involve only one soil order (Mulla and McBratney, 1999). The spatial variability of some soil properties is generally influenced by land use and management practices (Ebabu et al., 2020), topography, soil-forming characters, and soil depths, (Zhang et al. 2014; Behera and Shukla 2015; Rosemary et al., 2017; Vasu et al., 2017. The diversity of spatial characteristics of soil, including nutrients and soil fertility, is one of the main factors that need to be considered for good and appropriate agricultural management. Generally, soil properties exhibit high heterogeneity (Young et al., 2008) at different spatial scales and can also vary substantially under different land uses (Nadrowski et al., 2010). The spatial distribution of soil properties at different spatial scales has been extensively evaluated using geostatistical methods (Klatka et al., 2019; Rabi et al., 2014). Geostatistics and kriging tehniques have been used intensively in many studies of soil spatial data. Several studies have been carried out regarding the spatial chemical characteristics of paddy field soil, including Yanai et al., 2000, 2001, 2002; Young et al., 2002; Liu et al., 2008; Kamarudin et al., 2016). This research aimed to determine the spatial distribution of soil properties and the fertility status of paddy rice fields and create a kriged map of rice field fertility in Oransbari District, South Manokwari Region.

MATERIALS AND METHODS

Location of Study

This study was carried out in six villages (Sidomulyo, Margomulyo, Margorukun, Muari, Warbiadi, Akeju) of Oransbari District, South Manokwari Region, Papua Barat, which is at 134°12'30.15" to 134°14'31.60" E, and 1°18'18.73" to 1°21'8.77" S (Figure 1). The farm covers an area of 337,42 km^2 and is divided into 14 villages. The mean annual temperature was 19.8 ^{o}C (min) and 33 ^{o}C (max), and the annual rainfall was about 1.579 mm (BPS Papua Barat, 2023). The area is dominated by flats with some rolling hills. The major soil textures in this area are mainly medium loam, sandy loam, and clayey loam. The primary land use mainly consists of food crop cultivation and paddy-rice farming.

Soil Sampling and Analysis

Forty two composite soil samples were taken from the surface (0-30 cm). The soil sample points and sampling locations are presented in Figure 1. Soil samples collected from the research location were air-dried and sieved using a 2 mm sieve, and

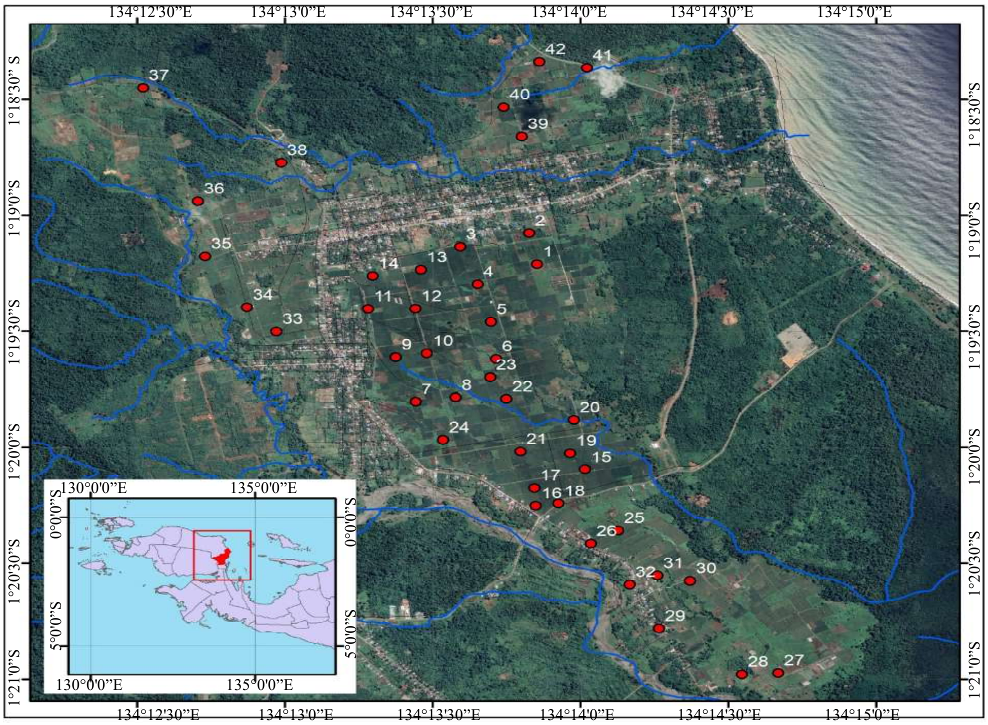

Figure 1. Study area and soil sampling point of paddy-rice field of Oransbari.

then 500 g of soil was taken for analysis in the laboratory. All samples were analyzed for soil chemical properties (i.e. N, P, K, pH, organic-C, total-N, C/N ratio, base saturation, CEC, and soil physical properties (i.e. soil texture). Soil property data from laboratory analysis is then used to classify soil fertility status according to the criteria for assessing soil chemical properties and criteria for determining the level of soil fertility status including cation exchange capacity, c-organic and macronutrients of nitrogen, phosphorus and potassium, and soil pH (PPT, 1995; Bagherzadeh et al, 2018; Sumarniasih et al., 2021).

Statistical Analysis

All soil variables were first examined for normality and variance of homogeneity. The statistical analysis of data involved (1) the distribution of data was characterized using conventional statistics (e.g. mean, minimum, maximum, median, standard deviation, skewness, kurtosis and coefficient of variation, and histogram), which assumes implicitly that observations are independent of one another regardless of their location in the sampled area; (2) geostatistical analysis was used to describe spatial dependency of soil characteristics at a farm scale. The spatial distribution of soil constituents was determined using geostatistical techniques. Autocorrelation analysis of soil data was performed using a semi-variogram to quantify the spatial dependence of the data points and to optimize the semi-variance analysis calculated an autocorrelation index (the semi-variance) among groups of pairs of samples separated by a given distance and produced a composite graph of the relationship between the semi variance among samples and the distance between samples (the semi-variogram) (Boerner et al., 1996).

From sparse samples data, kriging estimate the variables interest value at one or more unsampled points or over larger blocks. Kriging has been used extensively to describe spatial variability of soil characteristics (Yost et al., 1982; Webster, 1985). Maps were produced with GIS software ArcGIS 11, and the Spatial Analyst and Geostatistical Analyst extensions.

RESULTS AND DISCUSSION

Summary Statistics of Soil Properties

The summary statistics of mean, median, standard deviation, kurtosis, skewness, minimum, maximum, and coefficient of variation of soil pH, organic-C, total-N, C/N ratio, P, K, base saturation, CEC and soil texture across the farm is presented in Table 1. The soil at the study site had a mean soil pH of 6.34 (across the farm) and ranged from 5.83 to 6.93. In general, organic-C ranged from low to high and total-N were low across the farm. The

Table 1. Descriptive statistics of soil properties of paddy-rice field of oransbari.

Parameter/ n= 42	Mean	Median	Standard Deviation	Kurtosis	Skewness	Min	Max	Coefficient of Variation
- Sand	38.52	36	12.66	3.15	0.86	19	69	32.87
- Silt	45.33	46.5	8.15	3.45	-0.68	24	59	17.98
- Clay	16.143	17	8.44	2.73	0.15	1	42	52.28
Nitrogen	0.15	0.15	0.02	2.45	-0.49	0.11	0.17	13.33
Carbon	3.47	3.24	1.07	5.31	1.26	3.47	6.94	30.84
C/N	24.31	22.5	7.76	4.76	1.25	11	42	31.92
Phosphorus								
- Available	86.41	79.5	41.69	4.57	1.19	30	227	48.25
- Total	41.19	37	18.67	4.21	1.12	13	42	45.33
Potassium								
-Available	24.93	25	7.5	2.01	0.25	12	42	30.08
-Total	36.62	38	5.93	3.55	0.35	24	42	16.19
pH (H_2O)	6.34	6.24	0.35	1.77	0.34	5.83	6.93	5.52
Base Saturation	95.48	100	34.21	5.64	-1.79	74	100	35.83
CEC	39.06	39.74	7.14	3.17	-0.35	18.42	51.23	18.28

mean level of P in the soil was realtively high (86.41 mg kg^{-1}) and ranged from 30 to 227 mg kg^{-1}. This significant P variability indicated the high application of P fertilizer in some areas of the farm. The mean level of K across the farm was high (24.93 mg kg^{-1}). The coefficient of variation, which is a first approximation of heterogeneity at the sampling site varied among the soil variables and ranged from soil pH (5.52%) followed by total-N (13.33%), total-K (16.19 %), CEC (18.28 %), available-K (30.08%), organic-C (30.84%), C/N ratio (31.92%), base saturation (35.83%), total-P (45.33%), and available-P (48.25%), were the highest of coefficient of variation.

Spatial Analysis of Soil Properties

The semi-variogram models and best-fitted model parameters are given in Table 2. Spatial patterns of soil properties were consistent in all directions and were fitted with spherical and linear models. All soil characteristics showed a relatively high positive nugget effect. The small nugget variances of soil pH, organic-C and total-N showed slight variation at distances shorter than 500 m. The range for most of the semi-variogram models was about <500 m. A high positive nugget in some of the soil properties studied can be explained by sampling error, short-range variability, and unexplained and inherent variability. The spatial variability of some soil characteristics across the farm showed high spatial autocorrelation. A moderate weak spatial dependence was found for total-N (50 %), and available-P (56%), while available-K (93%) had weak spatial dependence. The variable was considered to have a strong spatial dependence if the nugget-to-sill ratio was less than 25%, moderate spatial dependence if the ratio was between 25 to 75% and weak spatial dependence if the ratio is >75% (Cambardella et al., 1994). In general, semi-variograms demionstrated the arrangement for every soil parameters and all variograms were consistently well organized with a comparatively high nugget effect.

Soil Fertility Status

According to the standards for evaluating soil fertility conditions (Table 3), there were two fertility statuses of paddy fields at the sampling location in Oransbari District such as medium soil fertility status at the paddy-rice field on land in Sindang Jaya, Sidomulyo and in Margomulyo Village and high soil fertility status in the areas of Muari, Margomulyo, Akeju, Sindang Jaya, and Sidomulyo. In moderate soil fertility status, the limiting factor was available-P and organic-C content which had low values, therefore the content of these two parameters must be increased through the addition of fertilizer and organic material.

Table 2. Semivariance analysis of the spatial structure of soil properties of a paddy-rice field of Oransbari.

Variable	Nugget	Sill	Relative Nugget effect	Spatial Dependence	Range	Model
	(C_0)	(C=C0+C1)	(C0/C)	(C1/C)	(m)	
Texture						
- Sand	52.89	172.36	0.31	0.69	21.66	Spherical
- Silt	0	82.97	0	1	37.35	Stable
- Clay	30.08	60.89	0.49	0.51	22.59	Stable
Nitrogen	0.0001	0.0002	0.50	0.50	56.75	Stable
C- Organic	0.6	0.61	0.98	0.02	11.81	Stable
C/N	30.36	39.47	0.77	0.23	14.35	Stable
Phosphorus						
- Available	687.91	1568.19	0.44	0.56	15.80	Spherical
- Total	191.21	245.31	0.78	0.21	12.77	Stable
Potassium						
- Available	6.06	81.66	0.07	0.93	21.18	Spherical
- Total	12.53	37.23	0.02	23.64	21.17	Stable
pH (H_2O)	0.11	0.19	5.79	-4.79	16.74	Stable
Base Saturation	38.72	14.52	2.67	-1.67	17.65	Stable
CEC	16.86	19.89	0.85	0.15	5.75	Stable

Table 3. Soil fertility status of paddy-rice field of oransbari.

No.	Sampling Point	CEC (me/100g^{-1})	BS (%)	Organic-C (%)	P_2O_5 HCl 25% (mg/100g^{-1})	K_2O HCl 25% (mg/100g^{-1})	Soil Fertility Status
1	S1	51.23***	79**	4.11**	72***	40*	High
2	S2	41.21***	99***	4.89**	32*	33*	High
3	S3	40.07***	88***	3.2**	38*	28*	High
4	S4	49.27***	90***	3.71**	44**	31*	High
5	S5	30.6**	100+***	2,95**	19-	24*	Medium
6	S6	38.33**	100+***	2.77**	38*	30*	High
7	S7	45.23***	92***	3.9**	15-	27*	Medium
8	S8	39.6**	100+***	2.86**	22*	28*	High
9	S9	42.85***	93***	3.34**	35*	32*	High
10	S10	39.14**	96***	3.19**	44**	32**	High
11	S11	34.07**	100+***	2.92**	39*	34**	High
12	S12	45.85***	93***	2.29**	39*	32**	High
13	S13	43.69***	96***	1.82-	47**	32**	Medium
14	S14	26.37**	100+***	2.85**	57**	36**	High
15	S15	41.23***	100+***	2.88**	46**	39**	High
16	S16	51.06***	74**	3.29**	54**	31**	High
17	S17	41.75***	100+***	4.11**	81(***	43***	High
18	S18	41.9***	98***	4.35**	45(**	39*	High
19	S19	42.68***	88***	3.84**	36*	35*	High
20	S20	41.4***	92***	2.67**	25*	39*	High
21	S21	49.16***	88***	2.85**	22*	38*	High
22	S22	42.97***	98***	2.65**	32*	33*	High
23	S23	37.51**	88***	2.5**	30*	40*	High
24	S24	47.11***	96***	1.47-	22*	30*	Medium
25	S25	47.3***	96***	3.25**	33*	35*	High
26	S26	36.78**	92***	4.25**	83***	33*	High
27	S27	31.98**	100+***	4.12**	53**	37*	High
28	S28	33.42**	100***	3.55**	44**	38*	High
29	S29	38.25**	100+***	3.61**	53**	38*	High
30	S30	33.97**	100+***	6.94***	34*	40*	High
31	S31	39.88**	100+***	6.55***	28*	39*	High
32	S32	34.21**	100+***	2.74**	31*	40*	High
33	S33	30.85**	100+***	5.03***	68***	49**	High
34	S34	33.04**	100+***	4.56**	99***	54**	High
35	S35	30.51**	100+***	4.46**	46**	43**	High
36	S36	51.17***	74***	2.7**	22*	40**	High
37	S37	18.42*	100+***	3.23**	13--	40**	Medium
38	S38	32.23**	100+***	3.38**	36*	43**	High
39	S39	33.72**	100+***	2.53**	33*	39*	High
40	S40	42.4**	100+***	3.01**	26*	42**	High
41	S41	33.29**	100+***	2.96**	36*	39*	High
42	S42	35.35**	100+***	3.52**	58**	43**	High

Note: * = Medium, ** = High, *** = Very High, - = Low, — = Very Low

Kriged map estimates of the spatial distribution of soil characteristics

The spatial distribution of soil characteristics was computed using the semi-variogram model (Figure 2). Consequently, samples collected in close proximity are more likely to exhibit high correlation than those taken further apart along the gradients. Therefore the plots appeared to be less structured spatially. Kriged maps revealed various spatial

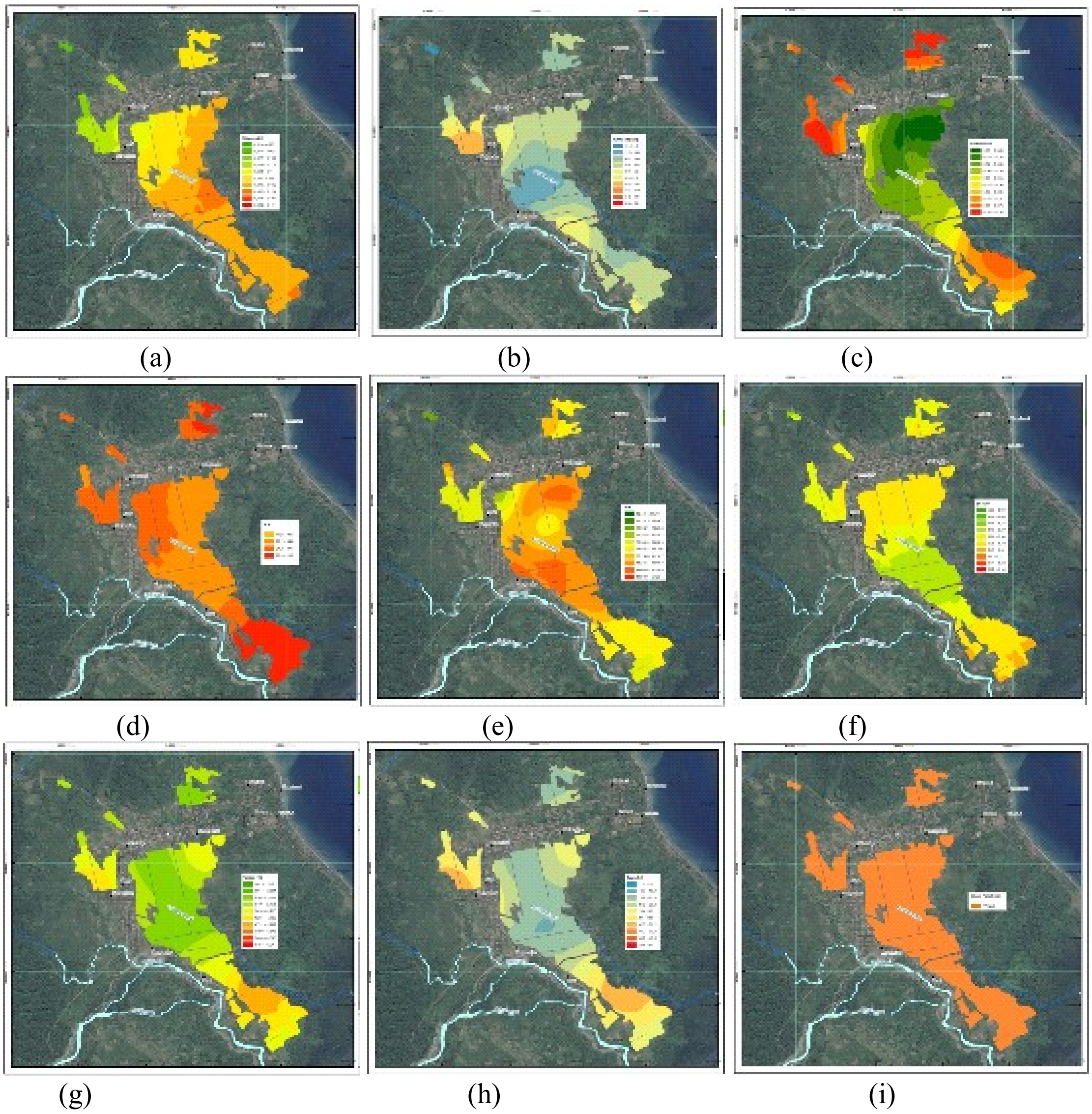

Figure 2. Spatial map of (a) total-N; (b) total-P; (c) total-K; (d) base saturation; (e) CEC; (f) pH (H$_2$O; (g) organic-C; (h) C/N ratio; and (i) soil fertility status of paddy-rice field of oransbari.

patterns across the range of soil properties assessed. A consistent trend was observed in soil characteristics across the areas. Almost all the patterns of soil properties were similar, as expected based on a high correlation among farms.

DISCUSSION

In general, the coefficient variation of soil pH corresponded with that of studies by Yost et al.(1982), Zhou et al. (1996) Tsegaya, Hill (1998) and Djuuna (2007) where soil pH had a lower variance compared to other soil properties because the pH values are based on log scale. In addition, low coefficient variation of soil pH was also related to the observation by Hillel (1980) that sand content, pH in water and pH in KCl had a low coefficient of variation (CV <10%), while C, N, and clay content had medium variation (CV 10-100%) (Mapa and Kumaragamage, 1996; Robertson et al., 1997; Castrignano et al., 2000; Yang et al., 2001; Conan and Paustian, 2002). Furthermore, some studies also explained that the spatial variation of soil pH is influenced by other factors such as topography (Tu et al., 2018), climate (Slessarev et al., 2016), parent material (Barton et al., 1994), and vegetation cover (Cannone et al., 2021). A lower variance in a broader areas may be linked to the homogeneity of land use patterns and other soil management practices (i.e. application of fertilizer and soil erosion). Furthermore, the high coefficient of variation in this study was the total-P (45.33%) and available-P (48.25%). This finding correlated with the study of Susanto and Sunarminto, 2013, that among the soil properties measured, available-P was high in coefficient of variation (77,11%), this might be influenced by internal and external factors of soil. Differences in variation of soil properties may also be attributed to previous management practices (e.g. slash and burn and cleared forest land (Cerri et al., 2004; Trangmar et al., 1987)). Pankhurst et al. (2002) demonstrated that the change in tillage and crop residue management practice affected some chemical and microbiological properties of soil, especially in the top 0-5 cm. In the present study, the information about agricultural practices on this farm was not clearly stated, because the farmer mainly used tillage practices and the application of fertilizer when the paddocks were used to grow crops other than paddy rice. It might be one of the reasons that some soil property values were higher in most areas. Soil properties such as texture can vary due to the natural differences of the parent material. Therefore, the change in land use pattern could affect soil properties, although this might not be consistent for different soil properties and soil types. This study demonstrated that spatial dependence on some soil properties can extend for relatively small distances. However, the lack of samples at shorter distances means that much of the variation in soil characteristics remained unexplained, therefore cannot be attributed to spatial variability at the scales investigated. Robertson and Gross (1994) noted that soil variables are likely to be characterized by more than one scale of variability as factors influencing variability operate at different scales. Vegetation, agricultural practices, and topography can influence the spatial dependence of soil properties in both short and long ranges.

The spatial distribution of soil characteristics was well structured, although some soil properties had a high nugget effect. There was considerable small-scale variation in the soil data, which may be attributed to either sampling density or errors and outliers. In other words, the sampling density was not intensive enough to reveal the spatial pattern of soil properties in the study area, and more samples across shorter distances may demonstrate this scale of variation. Various factor, including nutrient availability, pH levels, organic matter content, and soil texture, influence soil fertility. These factors are not uniformly distributed across a paddy field, leading to significant spatial variability (Cambardella et al., 1994). This variability can be attributed to both natural processes, such as topography and hydrology, and anthropogenic activities, including land management practices and irrigation techniques (He et al., 2007). As a result, certain areas within a paddy field may exhibit higher fertility levels, while others may be less conducive to rice growth.

In moderate soil fertility status, the limiting factor is the P_2O_5 and C-organic content which have low values, so the content of these two parameters must be increased through the addition of fertilizer and organic material. Phosphorus content in paddy soil after flooding can occur in two ways, namely phosphorus can increase greatly due to being tightly bound to soil particles and phosphorus is less reduced due to erosion. The important role of the P element means that this element must be available when planting rice. Overall, this study explained that most of the paddy-rice field areas in Oransbari had medium to high soil fertility status. However, medium and high soil fertility still requires fertilization based on the requirement of the paddy-rice plant.

CONCLUSIONS

This study's variability of soil properties exhibited spatial dependence that could be well-explained by semi-variogram models. Some soil properties exhibited spatial dependence at relatively short and long distances. The results may indicate the low variability and homogeneity of soil properties and land management at the study site. Variation in soil property might also be linked to the earlier management practices and land use patterns. Most rice paddy fields in Oransbari showed high soil fertility status, which indicated that high-yield rice production can be achieved for this region. However, land management factors should be considered for sustainable land use.

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