Spatial Variation of Soil Properties and Rice Yield on Recently Cleared Land[1]

B. B. TRANGMAR, R. S. YOST, M. K. WADE, G. UEHARA, AND M. SUDJADI[2]

ABSTRACT

Crop yields on cleared forest land of the humid tropics are often highly variable due to spatial heterogeneity of soil properties. This study aimed to characterize spatial variation of soil chemical properties and yield components of upland rice (*Oryza sativa*) on a 0.1-ha field of recently cleared land in West Sumatra, Indonesia. Plants were taller, grew and grain yields higher on sites where forest trash had been piled and burned, compared to the surrounding soils and other sites where topsoils had been removed. This pattern was largely caused by lower levels of Al saturation and higher concentrations of exchangeable cations in burned sites compared to other parts of the plot. The range of spatial dependence for soil acidity and exchange characteristics was 3 to 4 m, but increased to 7 m for organic C, total N, and extractable P. Semivariograms of crop components were better structured and had longer ranges (up to 20 m) than the soil chemical properties. Block kriging gave more precise local estimates of grain yield at unsampled locations than terrain unit means because it utilized the inherent structure of variation determined from quantitative spatial analysis of observed values. Block kriged values of grain yield ranged from 11 to 355 g/m^2 with estimation standard deviations ranging from 9 to 24 g/m^2, depending on distance of interpolated cells from the 122 sample locations.

Additional Index Words: geostatistics, semivariograms, block kriging, Al saturation, upland rice.

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SPATIAL VARIATION OF SOIL chemical and physical properties influences soil and crop management on recently cleared land in many parts of the humid tropics. Mechanical land clearance by bulldozing large trees and stumps may remove topsoils, expose high-Al subsoils, and cause compaction and structural deterioration of soils (Van Der Weert, 1974). Sites where forest trash is piled and burned commonly have higher fertility status and lower acidity than the surrounding soils (Seubert et al., 1977; Lal and Cummings, 1979). Such variation causes uneven crop growth, confounds treatment effects in field experiments, and decreases the effectiveness of uniformly applied soil management practices on a field scale (Kang and Moormann, 1977). Yield differences between bulldozed and burned areas may persist for several crops following land clearing (Seubert et al., 1977).

Uneven crop growth in experimental plots and farmers fields on cleared areas in Sitiung, West Sumatra, Indonesia, suggested that spatial variability of soil chemical and physical properties was an important variable to consider in planning soil management experiments in the region. Geostatistical analysis of within-field variation of important soil nutrient and plant growth parameters can help identify cause-effect relationships between these parameters (Tabor et al., 1984). Such analysis may also suggest management approaches for reducing the effects of soil variability on crop yield.

This study was undertaken to characterize spatial variation of soil chemical properties and yield components of upland rice (*Oryza sativa*) in a typical farm management unit on recently cleared land in Sitiung.

MATERIALS AND METHODS

Site Selection and Sampling

The study area of 784 m^2 was located in the Sitiung IIE transmigration settlement of West Sumatra, Indonesia (101°55′E, 1°10′S, 80 m above sea level). The site occurs on an undulating interfluve crest of a dissected Tertiary peneplain surface (Buurmann and Soekardi, 1980). The soil is a clayey, kaolinitic, isohyperthermic Tropeptic Haplorthox with a mean annual rainfall of 2750 mm.

Primary forest had been cleared from the area by bulldozing with a straight blade in 1977. This had been followed by intermittent burning of the remaining trash, large trunks, and stumps during 1977 to 1983. Surface features of the site included a series of ash piles 1 to 3 m in diameter, areas of exposed subsoil from which topsoil had been removed (3 to 4 m in diameter), and burned tree stumps interspersed with topsoils which varied in thickness and contained varying quantities of charcoal derived from burned sites (Fig. 1).

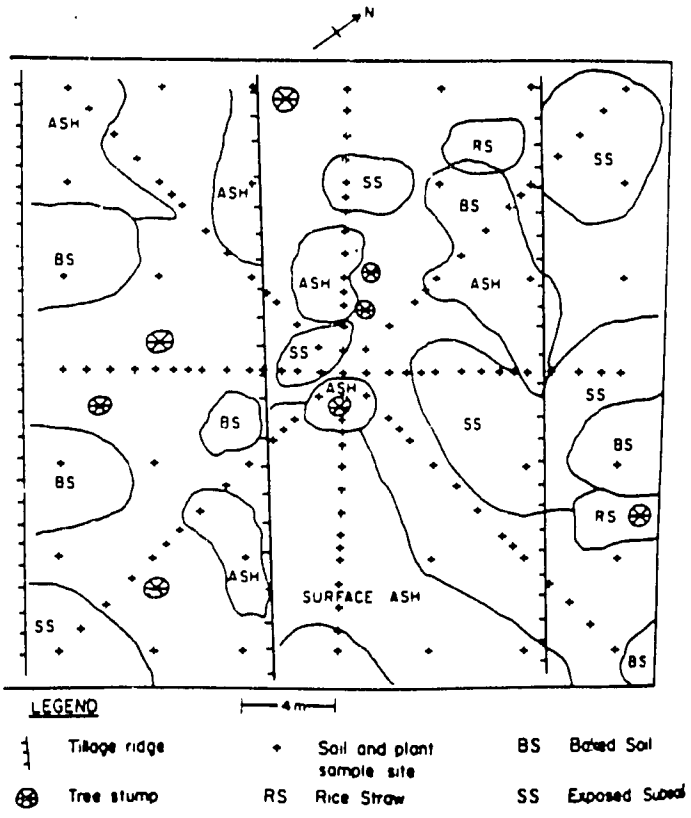

Fig. 1. Sampling for soil and plant measurements in relation to surface features of the site.

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Small areas (1–2 m in diameter) of aggregated soil baked by intense burning were also present.

Upland rice and cassava had been grown on the site during the period between land clearance in 1977 and soil sampling in July 1983. These crops had been grown during the rainy season (October–April) under rain-fed conditions with little or no fertilizer inputs. Weed removal and shallow tillage prior to planting were the only consistently applied management inputs during cultivation. The site had usually been left fallow during the dry season (June to August) of each year. Small patches of stubble from the previous upland rice crop were present on the plot and a series of tillage ridges 0.2 m high and 10 to 12 m apart had been prepared for planting of upland rice in the wet season of 1983 to 1984.

Soil samples of the 0- to 20-cm depth interval were collected at 137 locations in the plot (Fig. 1). Three auger samples within a radius of about 30 cm were taken at each location and bulked for analysis. Sample sites were located 4 m apart in a 28- by 28-m grid with additional samples taken along the main axes and diagonals of the grid at 1- and 1.4-m intervals, respectively (Fig. 1). Samples were also collected 0.5 and 0.7 m apart on each of the main axes and diagonals, respectively. This sampling pattern was designed to identify variation in different directions and to provide a range of distances between samples so that both short range and longer range variation could be identified. The plot size (784 m^2) was similar to the actual field area of many crops grown in the region.

Upland rice was grown on the site under rainfed and no tillage conditions without fertilizer during November 1983 to January 1984. The crop was planted using the planting stick method. Planting density was 16 hills per m^2, in a 25- by 25-cm grid. Four to six seeds were planted per hill. Mean plant height at 60 d after planting (DAP), stover and grain dry weight were measured over 121 1- by 1-m cells across the plot. Cell centroids coincided with the soil sample locations at the 1- and 1.4-m spacings along the main axes and diagonals of the grid shown in Fig. 1.

Laboratory Analyses

Sand, silt, and clay fractions were determined through sieve and pipette analysis. Soil pH was measured with a glass electrode in a 1:1 soil/water suspension. Organic C was determined by acid dichromate digestion and $FeSO_4$ titration (USDA, 1967). Total N was determined using semimicro-Kjeldahl methods (USDA, 1967). Available P was extracted with 0.5 *M* $NaHCO_3$ at pH 8.5 using the method of Olsen et al. (1954). Exchangeable cations were extracted with neutral 1 *M* NH_4OAc and determined by atomic absorption (Ca, Mg) and flame photometry (K, Na). Exchangeable Al was determined by extraction with unbuffered 1 *M* KCl and fluoride titration (USDA, 1967). Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable cations plus KCl-extractable Al. Aluminum saturation was calculated as (KCl-extractable Al/ECEC) × 100. Available Cu and Zn were determined by extraction with 0.1 *M* HCl (Cheng and Bray, 1953; Nelson et al., 1959).

Statistical Analysis

The approximation of each property to normal and lognormal probability distributions was determined using probability plots and the Kolmogorov-Smirnoff D statistic (Barr et al., 1979). Mean, standard deviation (SD), and coefficient of variation (CV) were determined for each soil and crop parameter. The Statistical Analysis System (SAS) (Barr et al., 1979) was used to perform linear correlation and multiple regression of crop parameters on soil properties to determine which soil properties most influenced crop growth and yield.

The presence of areas where forest trash had been piled and burned, areas of exposed subsoils from which topsoil had been removed, and surrounding areas where topsoils remained relatively undisturbed provided a logical grouping of samples from which to identify any systematic component of within-site variation. The within-site variability in soil and crop parameters explained by these "terrain" unit groupings was determined by unbalanced ANOVA and Students *t* test of mean differences.

Isotropic semivariograms (Burgess and Webster, 1980a) for each soil and crop parameter were computed to determine any spatially-dependent variance within the site. Semivariograms of each property were also computed in four different directions (N–S, NE–SW, E–W, SE–NW, each with direction tolerance of ± 22.5°) to examine for anisotropy. Semivariograms of lognormally distributed properties were computed on log values of the original data.

The semivariance at a given distance interval or lag, *h*, was estimated as the average of the squared differences between all observations, $z(x_i)$, separated by that lag, i.e.,

$$\gamma(\theta,h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_{i+h})]^2 \qquad [1]$$

where there are $N(h)$ pairs of observations per lag and θ is the azimuth of the line connecting locations x_i and $x_i + h$.

The "spherical" equation, weighted for the number of pairs in each lag, was fitted to experimental semivariograms using the SAS nonlinear algorithm (Barr et al., 1979) to obtain semivariogram parameters. The spherical equation is

$$\gamma(h) = \frac{3h}{2a} - \frac{h^3}{2a^3} \quad \text{when } h \le a$$
$$= C_o \quad \text{when } h \ge a \qquad [2]$$

where C_o is the spatial covariance, *a* is the range of spatial dependence, and *h* is the lag distance (Journel and Huijbregts, 1978). This model was selected over linear and Mitscherlich equations because of more favorable R^2 values, weighted residual mean squares, jackknifing results, and better visual fit over shortest lags when fitted to experimental semivariances of each property. The nugget variance, range and sill (Journel and Huijbregts, 1978) of each semivariogram were tabulated and provided the basis for interpretation of spatial dependence.

Spatial dependence of Al saturation and grain yield was used for local estimation of values at unsampled locations by block kriging (Burgess and Webster, 1980b). Values of Al saturation and grain yield were block kriged for 169 1- by 1-m cells arranged in a square grid across the site. The block size of 1 m^2 was an assumed average rooting area of annual crop plants in the study area. Three-dimensional surfaces of block kriged values for each variable and the estimation variances for grain yield were computed using the SPLOT algorithm (Bridges and Becker, 1976).

RESULTS AND DISCUSSION

Variation Among Terrain Units

All soil properties except pH, exchangeable Mg, Al, and Al saturation required log transformation prior to statistical analysis. Coefficients of variation ranged from 8% for clay content to 147% for exchangeable Ca, and generally exceeded 30%, indicating considerable within-site variability of most properties.

Soil chemical heterogeneity was partly explained by differences between burned sites, areas of exposed subsoil and the surrounding soils (Table 1). Organic C, total N, and extractable P all decreased in the sequence: burned patches > surrounding soil > exposed subsoil, although only the dif-

Table 1. Mean comparisons† of soil chemical properties among terrain units.

Soil property	Burn sites (n = 26)	Surrounding soil (n = 87)	Exposed subsoil (n = 24)
pH	5.0a	4.4b	4.1c
Organic C (%)	3.9a	3.4a	2.9a
Total N (%)	0.27a	0.24a	0.22a
$NaHCO_3$-P (μg g^{-1})	13c	9b	7c
Exchangeable cations (cmol$_c$ kg^{-1})			
Ca	3.9a	1.6b	0.6c
Mg	1.4a	0.6b	0.2c
K	0.5a	0.3b	0.2c
Exchangeable Al (cmol$_c$ kg^{-1})	1.3b	2.4a	2.8a
ECEC (cmol$_c$ kg^{-1})	6.9a	4.8b	3.9c
Al saturation (%)	26c	54b	73a
Cu (μg g^{-1})	2a	2a	2a
Zn (μg g^{-1})	3a	3b	1c

† Means within a row followed by the same letter are not significantly different (P = 0.05) according to Student's t test. T tests performed on log transformed values of all properites except pH, Mg, Al, and Al saturation. Arithmetic means reported for pH, Mg, Al and Al saturation, while means reported for log transformed properties are those re-expressed in terms of the original data using equations of Haan (1977).

ferences in extractable P among sites were statistically significant (Table 1). This general sequence probably arose from the collection of vegetation trash into small piles for burning, resulting in uneven preburn concentrations of C, N, P, and other elements across the plot. Volatilization losses may explain nonsignificant differences in C and N between burned sites and other areas (Table 1).

The distribution of nutrient cations (Ca, Mg, K) were positively related to pH (r = 0.81, 0.82, 0.71, respectively) and negatively related (r = −0.81, −0.85, −0.63, respectively) to Al saturation of the exchange complex. Cation concentrations and pH were all higher in the burned sites and decreased through the surrounding soils to areas of exposed subsoil (Table 1). Exchangeable Al and Al saturation of ECEC had the reverse trends. Given the pH-dependent charge of these soils, differences in ECEC among terrain units closely followed differences in soil pH. Release of cations from vegetation by burning (Sanchez et al., 1983) and improved CEC associated with higher pH and greater amounts of ash may explain higher cation levels in burned sites than in other areas. Zinc was also present in slightly higher concentrations in the burned sites although the amounts present were still low relative to critical levels for many crops (Cox and Kamprath, 1971). These differences in soil chemical properties among burn sites and exposed subsoils are consistent with those obtained by Seubert et al. (1977) between burned and bulldozed areas.

Differences in nutrient and Al concentrations among terrain units were reflected in plant height and yield of the upland rice crop grown on the site. Mean plant height and stover and grain weights were significantly greater on burned sites than on surrounding soils and exposed subsoils (Table 2). All three crop components were smaller on exposed subsoils than on surrounding soils although differences were not statistically significant (Table 2). Plant height and yield were positively correlated with the nutrient cations and Zn, but negatively correlated with exchangeable Al or Al saturation (Table 3). None of the crop components were correlated with total N or available P suggesting that variation of these properties explained little of the variation in rice growth and yield.

Multiple regression analysis indicated that soil chemical properties accounted for a maximum of 41% of variance in plant height, 33% of variance in stover yield, and 29% of variance in grain yield. Aluminum saturation alone accounted for 36%, 29%, and 23% of variance in plant height, stover and grain yield, respectively. This suggests that the significant correlation of exchangeable cations (Table 3) with

Table 2. Mean comparisons† of plant height, stover, and grain yield of upland rice among terrain units.

Terrain unit	Plant height at 60 d	Stover dry weight	Grain dry weight
	cm	g/m^2	
Burn sites (n = 24)	92.5a	328.3a	227.1a
Surrounding soil (n = 74)	78.5b	233.8b	166.5b
Exposed subsoil (n = 23)	71.2b	192.7b	146.0b

† Means within a column followed by the same letter are not significantly different at P = 0.05 according to Student's t test.

Table 3. Coefficients of correlation (r)† of soil chemical properties with plant height and yield components of upland rice.

Soil property	Plant height at 60 d	Stover dry weight	Grain dry weight
	cm	g/m^2	
pH	0.51	0.44	0.38
Organic C (%)	−0.07^{ns}	−0.02^{ns}	0.02^{ns}
Total N (%)	0.09^{ns}	0.11^{ns}	0.14^{ns}
$NaHCO_3$-P (μg g^{-1})	0.60^{ns}	0.11^{ns}	0.11^{ns}
Exchangeable cations (cmol$_c$ kg^{-1})			
Ca	0.56	0.55	0.49
Mg	0.52	0.45	0.40
K	0.41	0.38	0.46
Exchangeable Al (cmol$_c$ kg^{-1})	−0.55	−0.47	−0.41
Al saturation (%)	−0.56	−0.51	−0.41
Cu (μg g^{-1})	0.07^{ns}	0.09^{ns}	0.12^{ns}
Zn (μg g^{-1})	0.42	0.34	0.33

† All r values significant at P <0.01 unless otherwise indicated. ns = nonsignificant at P = 0.05.

plant height and yield components is confounded by negative correlation of cations (r = −0.81, −0.85, −0.63, respectively) with Al saturation. In addition to toxic levels of Al, low soil and foliar levels of nutrient cations, particularly Mg, probably contributed to lower rice yields on area where topsoil had been removed.

Inhibited root growth and subsequent reductions in water and nutrient uptake are frequent effects of Al toxicity on plant growth (Sanchez, 1976). Plant height, and stover and grain yields all began to decrease when Al saturation exceeded about 45% of ECEC (2.0 cmol$_c$ Al/kg soil). On burned sites, Al saturation averaged <30% and nutrient cations were in adequate supply and favorable balance (Ca = 67%, Mg = 24%, K = 9% of total bases, respectively). In contrast, Al saturation exceeded 50% and levels of nutrient cations were markedly less in soils of surrounding areas where significant yield reductions occurred (Table 2). These adverse conditions became more evident in areas of exposed subsoil. Increased Al saturation of exposed subsoils was caused partly by slightly increased exchangeable Al but largely by decreased exchangeable cations (Table 1).

The variance unexplained by regressing crop parameters on soil chemical properties indicates that factors other than Al also influenced crop growth, particularly stover and grain yield. Differences in soil physical properties such as root impedance, available water, and infiltration rate might be expected to occur between burned sites and exposed subsoils, thus affecting water and nutrient uptake by crops (Van Der Weert, 1974; Seubert et al., 1977).

Spatial Dependence of Soil Properties and Plant Components

Despite significant differences in many soil and crop parameters among terrain units, the amount of total variance explained by such groupings was quite small.

Table 4. Spatial dependence of selected soil properties.†

Property	Range, m	Nugget variance	Percent of sill	Sill	Sample variance	R^2 of spherical model‡
Sand (%)	3.9	0.003	3	0.86	0.105	0.73**
Silt (%)	No pattern	–	–	–	16.8	–
Clay (%)	3.7	0.001	17	0.006	0.011	0.53*
pH (H_2O)	4.1	0.015	4	0.356	0.366	0.52**
Organic C (%)	7.2	0.014	10	0.148	0.170	0.50**
Total N (%)	7.3	0.022	28	0.078	0.083	0.40**
0.5 *M* $NaHCO_3$-P	7.2	0.153	58	0.265	0.241	0.24*
Exchangeable cations ($cmol_c$ kg^{-1})						
Ca	No pattern	–	–	–	1.32	–
Mg	4.3	0.003	1	0.411	0.650	0.51**
K	No pattern	–	–	–	0.397	–
Exchangeable Al ($cmol_c$ kg^{-1})	4.0	0.388	26	1.504	1.88	0.52**
ECEC ($cmol_c$ kg^{-1})	3.0	0.018	20	0.089	0.089	0.67**
Al saturation (%)	3.9	174.0	2	723.4	905.4	0.57**
Cu ($\mu g/g^{-1}$)	7.4	0.025	35	0.072	0.084	0.30**
Zn ($\mu g/g^{-1}$)	<0.5	0.270	100	0.270	0.270	–

*,** = Significant at $P < 0.05$, 0.01, respectively.
† Semivariances for sand, clay, organic C, total N, $NaHCO_3$-P, exchangeable Ca, K, ECEC, Cu, and Zn computed on log transformed values.
‡ $R^2 = (SS_{corrected} - SS_{residual})/SS_{corrected}$.

The maximum SS total accounted for by SS among terrain units for any variable was only 28% (for exchangeable Ca). The resulting large within-unit variances diminish the precision of terrain units means in estimating location-specific values.

The assumption of classical statistics that deviations about the mean have a random geographic distribution does not consider the widely found spatial dependence of soil properties (Burgess and Webster, 1980a). Regionalized variable theory (Journel and Huijbregts, 1978) was applied to augment the classical approach by using spatial dependence among samples for local interpolation by block kriging.

Analysis of spatial dependence using semivariograms indicated that variation of soil properties and crop components was generally isotropic. Directional semivariograms of most properties were poorly structured. Only those of organic C and total N indicated any anisotropy, with maximum variation occurring along a SE–NW axis. Anisotropy ratios for these two properties were not large (1.6 and 1.8, respectively) and probably indicate a weak directional component in the land clearing methods or subsequent soil management.

The spherical model, weighted for the number of pairs in each lag, provided good estimation of the isotropic semivariogram parameters as indicated by significant coefficients of determination for all properties (Table 4). The number of sample pairs per lag ranged from 20 (0.5-m lag) to 218 (5.0-m lag). Sill values of the estimated semivariograms were generally similar to the sample variance for most soil properties (Table 4), indicating a general absence of trends across the site.

The ranges of spatial dependence of sand, clay, pH, exchangeable Mg, Al, ECEC, and Al saturation were 3.0 to 4.1 m (Table 4). This distance approximates the diameter of burned sites and areas of exposed subsoil (Fig. 1). This suggests that spatial dependence of these properties and distribution of terrain units are probably determined by the land clearing, burning, and

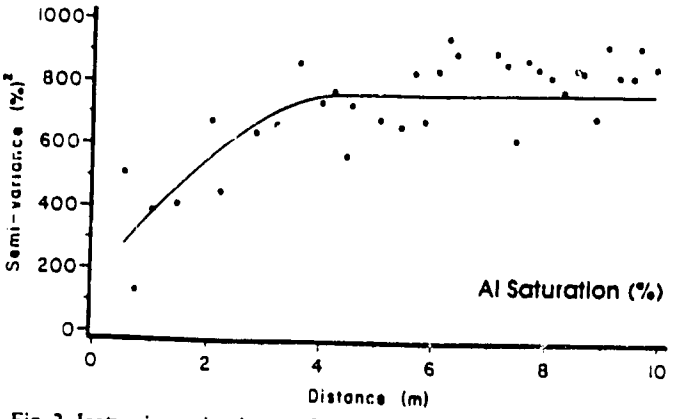

Fig. 2. Isotropic semivariogram for Al saturation, 0- to 20-cm depth.

subsequent soil management practices imposed on the site.

The small nugget variances of sand, clay, soil acidity, and exchange characteristics (Table 4) suggest little variation was present at distances shorter than the first lag (0.5 m) of the semivariograms. This indicates that the sampling scheme used was adequate to quantify spatial dependence of these properties. The good fit of the spherical model and small nugget variances suggest that local variation is generally continuous and gradational rather than abrupt despite some significant mean differences among terrain units when analyzed on a whole-plot basis. This confirms the presence of local or "quasi-stationarity" (Journal and Huijbregts, 1978) at short distances of separation within the site. However, some abrupt differences among sample values did also occur locally, causing large semivariances at short lages for some properties, such as Al saturation (Fig. 2).

Ranges of spatial dependence for organic C, total N, $NaHCO_3$-P and Cu were between 7.2 and 7.4 m (Table 4). Organic C, total N, and Cu did not vary significantly among terrain units (Table 1) and although $NaHCO_3$-P did, the absolute differences were quite small. The more continuous nature of these properties may account for their longer ranges of spatial dependence compared with those of soil acidity and exchange characteristics.

Significant correlation of total N and $NaHCO_3$-P with organic C (r = 0.83, 0.48, respectively) suggests their spatial distribution was largely associated with that of organic material. Some of the organic material from the burn patches had been redistributed across the soil surface which may explain the longer ranges

Table 5. Spatial dependence of plant height and yield components of upland rice

Crop component	Range, m	Nugget variance	Percent of sill	Sill	Sample variance	R^2 of spherical model‡
Plant height (cm) at 60 d	19.9	154.0	29	538.5	442.0	0.87**
Stover dry weight (g/m^2)	15.3	14 683.2	62	23 675.9	22 451.1	0.40**
Grain dry weight (g/m^2)	18.5	6 041.4	55	10 939.9	10 144.9	0.66**

** = Significant at $P < 0.01$.
† $R^2 = (SS_{corrected} - SS_{residual})/SS_{corrected}$.

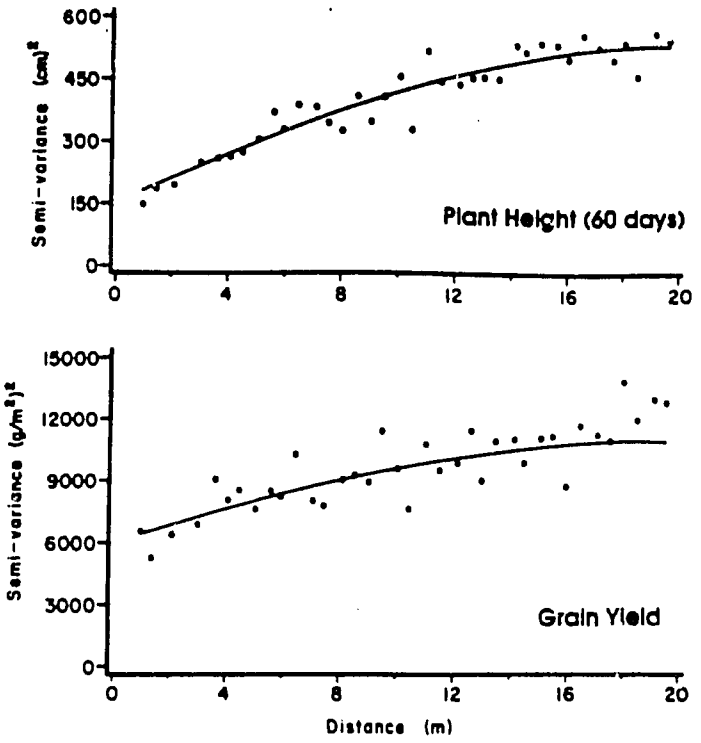

Fig. 3. Isotropic semivariogram for plant height at 60 d growth and grain yield of upland rice.

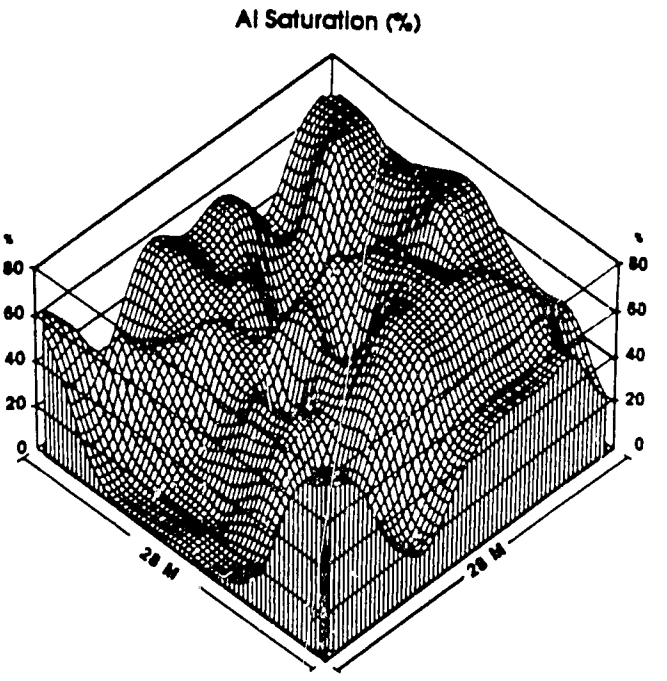

Fig. 4. Three-dimensional diagram of Al saturation (%) block kriged over one m² cells, 0- to 20-cm depth.

of organic C, N, and P semivariograms and only minor differences among terrain units. Long ranges of Cu semivariances and lack of terrain unit differences may be due to the generally low levels of Cu in the site rather than to any differences caused by management. Total N, $NaHCO_3$-P, and Cu had larger nugget variances (percent of sill) than the acidity and exchange characteristics implying more short range variation (Table 4).

The isotropic semivariances of silt, exchangeable Ca, and K showed no structure (Table 5) indicating extreme heterogeneity at the sampling scale used. The isotropic semivariogram for Zn showed pure nugget effect implying that any spatial dependence present occurs over very short distances (<1.0 m).

Semivariograms of the crop components (Fig. 3) showed greater continuity and longer ranges than those of the soil chemical properties. This may result from the larger sampling units (1 m²) for crop components and the characteristic of plant roots to integrate over a considerable soil volume, thus reducing the effects of short range soil variability on crop growth and emphasizing longer range phenomena. The ranges of spatial dependence obtained by weighted least squares (Table 5) exceed visually estimated ranges (Fig. 3) by about 5 m because the semivariances approach the sill gradually, and considerable deviations of the experimental semivariances occur about the estimated model. Such deviations are reflected by smaller coefficients of determination for yield components compared to plant height (Table 5). A weak trend effect at large lags may also be present. Large nugget variances of semivariograms (Table 5) was caused by microvariability of crop parameters within the 1-m² sampling surface.

Interpolation by Block Kriging

Values of Al saturation, plant height, and yield components were block kriged over 1 m² cells at 169 locations in a square grid over the site. The semivariogram range of 3.9 m was used as the kriging radius for Al saturation. This radius resulted in a minimum of two neighbor samples for some blocks on plot boundaries and a maximum of 29 at the plot center. A kriging radius of 7.2 m for grain yield was used to avoid any longer range nonstationary effects and still provided at least nine neighbor samples for each interpolated cell.

Block kriged values in Fig. 4 and 5 demonstrate the negative spatial relationship of Al saturation with rice grain yield. Kriged values of Al saturation ranged from 1 to 79% and those of grain yield from 11 to 355 g/m². The spatial pattern of kriged values for plant height and stover yield demonstrated a negative relationship with Al saturation similar to that of grain yield. High values of Al saturation generally coincided with small plants and low yields, particularly in the areas of exposed subsoil, that ran diagonally from east to west across the site and in the north and south corners. Conversely, the largest plants and the highest stover and grain yields occurred where Al saturation was lowest (Fig. 4), notably in burned sites.

The geometric pattern of estimation variances for grain yield (Fig. 6) directly reflects the sampling design used. The pattern is consistent with the premise of kriging theory that the reliability of interpolation depends on distance between sample locations and not on actual differences between sample values (Journel and Huijbregts, 1978). Small estimation variances in Fig. 6 mark interpolated cells containing samples while larger values mark cells more distant from sample sites. The large value at the center of the NE boundary of the site (Fig. 6) is caused by a missing sample at the

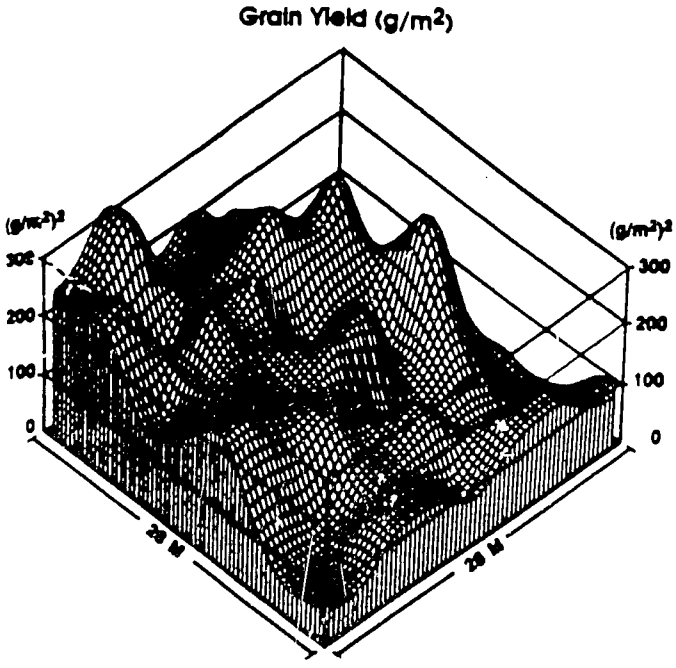

Fig. 5. Three-dimensional diagram of rice grain yield (g/m²) block kriged over one m² cells. Units are (g/m²)².

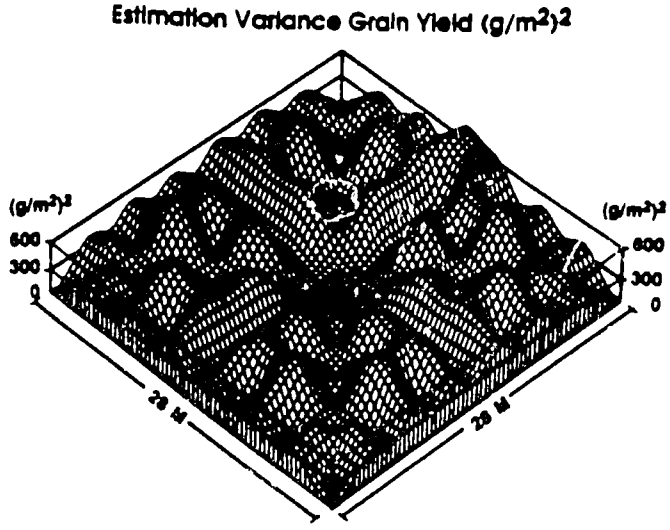

Fig. 6. Estimation variances for rice grain yield block kriged over one m² cells. Units are (g/m²)².

location. Except for that location, estimation variances range from 77 to 596 giving estimation SD of 8.8 to 24.4 g/m². These values are considerably less than the SD (94.1, 104.7, 96.7 g/m²) of the means for grain yield in burned sites, areas of exposed subsoil and surrounding soils, respectively. This demonstrates an improvement in local estimation precision achieved by block kriging compared to the classical statistical approach.

Effects of Spatial Variability on Experimental Design

Effect of the large microvariability on a field experiment was tested by laying out four replicates of seven potential treatments in a randomized complete block design across the site. Individual plot size was 4 by 7 m. Sample values of grain yield and Al saturation from 1-m square cells in each plot were averaged to obtain means for each of the 28 plots. This is analogous to the common practice of bulking samples for analysis on a whole plot basis. A large experimental error (CV of 37%) resulted in nonsignificant differences among treatment means of yield estimates which ranged from 1.00 to 2.08 Mg/ha with a Waller-Duncan LSD of 1.08 Mg/ha. Statistical analysis on a whole-plot basis masked the large within-plot variability of grain yield which ranged from 0.11 to 3.55 Mg/ha when considered on a 1-m square basis. Such variability was not shown by analysis of treatment means because the variation is averaged within each plot and because of the large error term that was partly due to significant variation among replicates. Similarly, the large variability of Al saturation (CV of 58%) within plots was masked by averaging on a whole plot basis.

Liming and P experiments conducted on similar soils in other cleared areas of West Sumatra by the present authors were unable to obtain treatment differences due to within-plot variability similar to that described here. Subsampling and analysis of yield components and soil properties on a microplot basis might be one way of interpreting such variation so that meaningful experimental results are still obtained. This study shows that detailed studies of soil properties in heterogeneous sites can help identify causes of such variability and suggest ways of accommodating it in experimental design and soil management.

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Effects of Phosphorus and Acidity on Levels of Silica Extracted from a Palouse Silt Loam[1]

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ABSTRACT

Concentrations of Si found in soil solutions are affected both by soil pH and by P availability. Consequently, it was hypothesized that the heavy local use of NH_4-based N fertilizers and of P fertilizers could greatly affect the Si chemistry of soils from the Palouse area of northern Idaho. The objectives of this study were to evaluate the effects of P and acidity on concentrations of Si in water extracts from Palouse silt loam (fine-silty, mixed, mesic, Pachic Ultic Haploxerolls) soils and to correlate observed effects with possible mechanisms responsible for Si solubility. Soil samples were equilibrated with acid and with P for periods of 0.2 to 150 d in 0.02 *M* $CaCl_2$ solutions. Increased acidity and the presence of P were both found to increase the concentrations of Si in solution above control levels. These data appear to be additive, suggesting that the mechanisms responsible for increasing solution Si levels for the respective treatments are different. It is postulated that acidity increases Si concentrations in solution by directly affecting the solubility of compounds containing Si, and that P oxyanions compete directly with Si compounds for specific sorption sites.

Additional Index Words: Si sorption, pH change, P extractable :, water-soluble Si.

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INCREASED USE OF NH_4-BASED N and of P fertilizers in farm management systems during the last 25 yr has affected the chemistry of surface soils in the Palouse area of northern Idaho and eastern Washington. Nitrification of NH_4-based fertilizers has acidified the surface 25 cm of soils in the region (Mahler, 1981; Mahler and Harder, 1984). This acidification has resulted in reduced plant productivity (Mahler and Harder, 1984) and increased levels of soluble Si in these soils (Douglas et al., 1984).

Douglas et al. (1984) found that levels of soluble Si in Palouse area soils were at least three times greater than values reported by McKeague and Cline (1963c). They also found that Si movement in the surface 15 cm of an acidified (by N fertilizer) Walla Walla (Typic Haploxeroll) silt loam was higher than at more alkaline lower profile depths. Barker and Scrivner (1985) found similar results and noted that Si concentrations in solution increased upon wetting, following periods of drying. The concentration of Si in soil solutions appear to be controlled by dynamic processes. Consequently, kinetics may be the controlling factor for maintaining soluble-Si levels in solution (Hallmark and Wilding, 1982).

An inverse relationship between pH and Si concentration of soil solutions was shown by Raupach (1957). His data are consistent with observations by other investigators (Beckwith and Reeve, 1963, 1964; McKeague and Cline, 1963a). Beckwith and Reeve (1963) found that the Si concentration in acid suspensions exceeded levels initially added because of a net Si release associated with the acid conditions. They hypothesized that some sorption phenomenon was primarily responsible for the soluble Si concentration. In subsequent studies (Beckwith and Reeve, 1964) with several anions, they concluded that pH rather than the presence of competing anions in solution was the primary causitive agent for the release of Si into solution. They concluded that specific sorption of Si compounds was responsible for controlling solution levels of Si.

Phosphorus has also been shown to significantly increase soil solution concentrations of Si (Low and Black, 1950; Birch, 1953; Reinfenberg and Buckwold, 1954; Raupach and Piper, 1959; Hingston and Raupach, 1967; Obihara and Russell, 1972). Demolon and Bastisse (1934) found P to be readily displaced from soils by anions such as tartrate, citrate, and silicate, but relatively unreplaceable by others (e.g., chloride, nitrate, and sulfate). This provided initial evidence that Si and P may compete for the same specific-sorption sites. The existence of specific anion sorption was substantiated by research efforts of Hingston et al. (1967, 1972) and of Jepson et al. (1976), which demonstrated ligand exchange of anions on geothite surfaces. This relationship was also supported by Obihara and Russell (1972). Raupach and Piper (1959) showed

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