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Spatial Variability of Tugbok Clay Loam in a Coconut-Based Farming System (CBFS) in Davao City, Philippines

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Abstract

The spatial distributions of soil physico-chemical properties were evaluated using variogram and kriging. Kriging as an interpolation technique that used variogram model of observed values was employed to determine values of a soil property at unsampled locations of the study area. Spatial variability map was then generated from the 'kriged' data points.

Spatial variability analysis using variogram of soil properties showed spatial patterns of various levels. Spatial dependence appeared moderate for soil pH and total K in the topsoil (0-15 cm) and in subsoil (15-30 cm), weak for Bray P in the topsoil but strong for bulk density and organic matter and depth of the topsoil. Spatial variability maps of soil properties showed that the area is strongly acidic, low in organic matter and Bray P, high in total K with low bulk density values at 1.2 to 1.29 (g cm^{-3}) and medium depth topsoil.

Spatial variability maps generated by kriging are expected to provide information in precision agriculture in order to make better management decisions, reduce chemical and fertilizer costs through more efficient application, provide more accurate farm records, improve crop yield, and reduce agro-chemical pollution. Precision agriculture relies on the existence of in-field variability.

Keywords: Kriging, soil properties; spatial variability; variogram.

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Introduction

Coconut is grown as a major crop in 64 out of 78 provinces in the Philippines and accounts for 60% of the world's coconut oil market. To ensure a regular supply of coconut oil will be a key challenge. There is a need to carry out significant soil fertility management in order to guarantee sufficient supply.

In the Philippines, information on soil variability has been very limited in the past because of lack and poor access to technology that evaluate spatial soil variability for efficient soil fertility management. With the wide range of geostatistical software available presently, data processing by means of geostatistical tools presents no problems for users without a special mathematical education. However, it should be noted that the choice of point samples and positioning of sampling sites on the plan of the territory are essential requirements for the application of geostatistics. The application of geostatistics in soil science ensures a quantitative description of the spatial variation of soils, improves accuracy in estimating soil properties for data interpolation and map compilation.

The spatial dependence of a soil property within the region can be modeled or described quantitatively using a variogram. Geostatistical technique known as kriging that make use of the variogram is then used to map the spatial distribution of a variable or in particular, a soil property. Kriging has the advantage of creating a detailed spectral soil map by interpolating unsampled locations (Ahn et al., 1999).

Results of soil analysis can be used to develop georeferenced maps showing the spatial variability of soil properties that delineate areas that would benefit from different management or identify areas of particular concern. In addition, maps of soil fertility, generated using geostatistics are important tools in precision agriculture. It is along this line that this study is conceived to fill in such knowledge gaps. This study aimed to investigate the spatial distribution of soil physico-chemical properties in Bago Oshiro, Davao City, Philippines.

Material and methods

Location and description of the study site

The study site is a four-hectare area located at Philippine Coconut Authority–Davao Research Center, Bago Oshiro, Davao City. Bago Oshiro is an elevated inland area of Davao City and the soil is mapped as Tugbok clay loam (Bureau of Soils, 1974). It is a reddish brown soil derived from igneous rocks of Mt. Apo with an undulating to gently sloping relief. Both external and internal drainage are good.

Soil sampling and analyses

Soil samples were taken from the topsoil (0-15 cm) and subsoil (15-30 cm), respectively. Each soil sample was analyzed for pH, Bray P, total K and organic matter. The sampling point was located at the center of the four sample palms. Coordinate locations of each sampling point were georeferenced using a Global Positioning System (GPS).

Statistical analysis, interpolation and mapping

Mean and coefficient of variation (CV) were determined for each soil property. In the geostatistical analysis, a variogram was used to evaluate the spatial variability of the soil properties. Variogram analysis consists of the experimental variogram calculated from the data and the variogram model fitted to the data. The variogram model is chosen from a set of mathematical functions that describe spatial relationships. The appropriate model is chosen by matching data points of the experimental variogram to the shape of the curve of the mathematical function. The range is the zone of influence (A1), a distance beyond which there is no spatial autocorrelation. The sill (C1) is the sample variance, a value of which the plotted points level off minus the nugget, while the nugget (C0) corresponds to the sampling error. Results of the variogram modeling were used in kriging to determine unsampled locations. Using the output of kriging, spatial variability maps were developed.

Results and discussion

On selected soil properties

On the average, the topsoil of the area had a depth of 15 cm, loose soils (1.27-1.29 g cm^{-3}), low organic matter content (2.1-3.5%) and Bray P (5-14 ppm) as shown in Figures 1 and 2. However, the site had high total K (>150 ppm), thus having adequate quantities to supply the needs of the palms (Magat, 1976).

In Figure 2, the topsoil and the subsoil also revealed a strong acidity (5.0-5.6), an indication of long term use of ammonium sulfate as one of the recommended fertilizers for coconut. Fortunately coconut can tolerate wide range of soil pH from pH 5.0-8.0 (The Coconut Committee, 1992) though the ideal pH range for optimum growth is 5.5-6.5. Soils having pH below 5.5 are commonly low in major soil nutrients such as phosphorus as shown in Figure 8. Soil P may be present in a form that is not available to plants. Acid soil conditions also affect the activity of micro-organisms responsible for breaking down organic matter. Further, the topsoil has higher values of Bray P, total K and organic matter content than the subsoil. Soil P and K are immobile nutrients. Soil P is extremely immobile in the soil, whereas, soil K has limited movement in the soil. Likewise, soil organic matter content decreases with soil depth.

The variation of the soil chemical attributes were analyzed by the criteria of Warrick & Nielsen (1980). Coefficient of variation (CV) for bulk density, depth of the topsoil, organic matter content, Bray P and total K was low (<12%). The highest and lowest CVs were related to Bray P (1.123) and bulk density (0.011) of the subsoil, respectively (Table 1).

Generally, CV values for selected soil properties are lower than those reported in other references, indicating probably to the homogenizing effect of the long-term coconut cultivation and homogenous management on topsoil. This finding is also in accordance with that of Paz Gonzalez et al. (2000).

Table 1. Coefficients of variation of soil physico-chemical properties in Bago Oshiro, Davao City, Philippines (n=89)

Soil Property	Coefficients of variation (%)	
	Topsoil	Subsoil
Bulk density	0.012	0.011
pH	0.026	0.022
Organic matter	0.263	0.350
Bray phosphorus	0.495	1.123
Total potassium	0.345	0.329
Depth of topsoil	0.169	-

Structure of spatial variability

The spatial variation of the soil properties within the examined area was quantified by using a variogram. Soil pH, Bray P, total K, depth of topsoil and bulk density were described with the spherical variogram model, with the exception of organic matter which is described by the gaussian model. The spherical (a) and gaussian (b) variogram models are shown in the following equations, respectively:

$$\gamma(h)= C_o + C_1\ [3h/2\ A_1 - 1/2(h/\ A_1)^3],\ h\leq A_1 \qquad (a)$$

$$\gamma(h)= C_o + C_1,\ h> A_1$$

$$\gamma(h)= C_o + C_1[1 - \exp(-3h^2/\ A_1^2)] \qquad (b)$$

In Tables 2 and 3, the parameters of the fitted variograms for the selected soil properties are listed.

Table 2. Parameters of model variograms fitted to the experimental variograms of topsoil physico chemical properties (n=89)

					Akaike		

Soil Property	Model Variogram	Nugget Variance (C_o)	Sill Variance (C_1)	Range (M) (A_1)	Information Criterion (AIC)	Spatial Ratio* (%)	Spatial Class**
Bulk Density (g cm^{-3})	Spherical	0.000063	0.000219	103.5	-234.4	22.3	Strong
pH	Spherical	0.012570	0.008824	80.1	-86.8	58.8	Moderate
Organic Matter (%)	Gaussian	0.013260	0.35020	117.6	-54.0	3.6	Strong
Bray Phosphorus (ppm)	Spherical	5.0	1.0	20.9	13.0	82.9	Weak
Total Potassium (ppm)	Spherical	14732	25924.0	86.3	200.2	36.2	Moderate
Depth (cm)	Spherical	0.00	8.7	21.4	20.4	0.0	Strong

* Spatial ratio=(nugget semivariance / total semivariance)100, total semivariance=nugget + sill
**Spatial dependence class ratio (Cambardella et al., 1994)
<25% =Strong spatial dependence
>25-75% =Moderate spatial dependence
>76% =Weak spatial dependence

Table 3. Parameters of model variograms fitted to the experimental variograms of subsoil physico chemical properties (n=89)

Soil Property	Model Variogram	Nugget Variance (Co)	Sill Variance (C1)	Range (M) (A1)	Akaike Information Criterion (AIC)	Spatial Ratio* (%)	Spatial Class**
Bulk Density **(**g cm^{-3})	Spherical	4.80E-05	0.000152	77.9	-240.3	23.9	Strong
pH	Spherical	0.009380	0.003731	77.0	-118.0	71.5	Moderate
Organic Matter (%)	Gaussian	0.077930	0.04045	67.7	-88.8	65.8	Moderate
Bray Phosphorus (ppm)	Spherical	7.9	5.6	87.1	33.8	58.5	Moderate
Total Potassium (ppm)	Spherical	16437	8002.6	49.7	146.8	67.3	Moderate

* Spatial ratio=(nugget semivariance / total semivariance)100, total semivariance=nugget + sill
**Spatial dependence class ratio (Cambardella et al., 1994)
<25% =Strong spatial dependence
>25-75% =Moderate spatial dependence
>76% =Weak spatial dependence

Figure 1. Mean values of selected soil physical properties

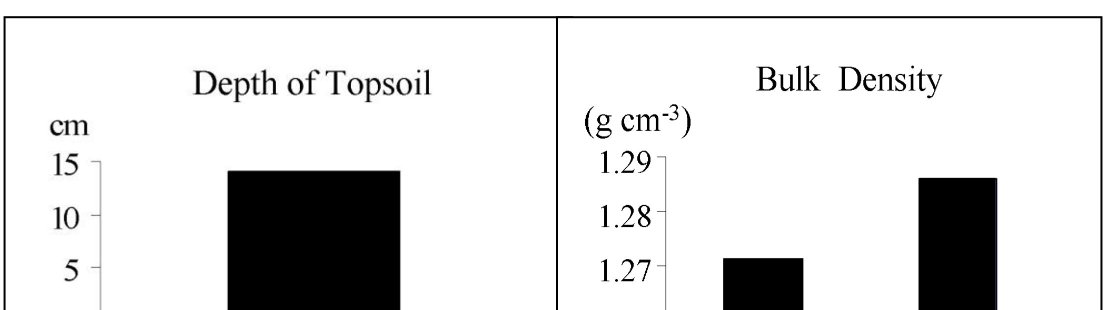
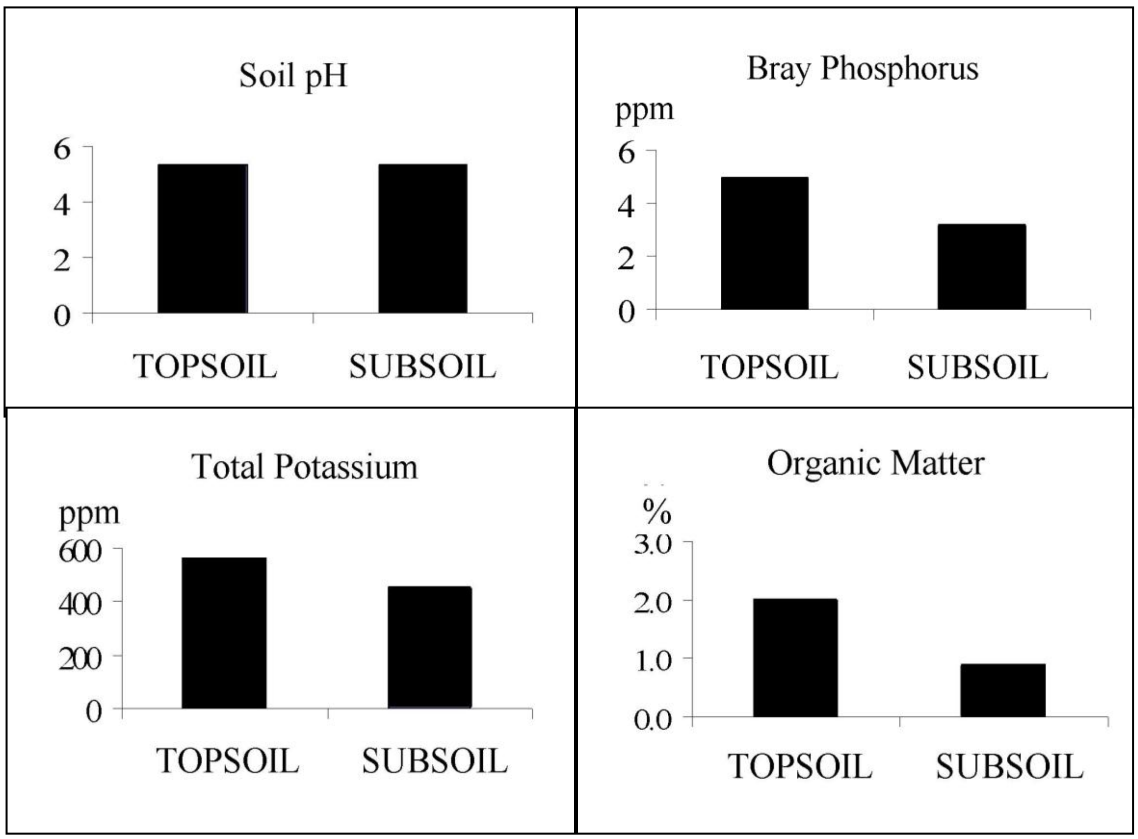


Figure 2. Mean values of selected soil chemical properties



Nugget variance is a function of the variability within the sample. It is a measure of the amount of variance due to errors in sampling, measurements and other unexplained sources of variance. Bulk density, depth of topsoil, pH and organic matter has nugget variances approaching zero except for Bray P and total K.

Total K showed a high nugget of 14732 ppm and 16437 ppm for topsoil and subsoil, respectively. Further, Bray P has nugget variances of 5 ppm and 8 ppm for topsoil and subsoil, respectively. Smaller nugget variances indicate that the sampling interval reflects the variance. A nugget effect near zero indicates that the relationship of spatially separated measurements within the range is strong. Many soil properties have non-zero nugget effect, which is caused by measurement error or micro-variability that can't be detected at the scale of sampling (Trangmar et al., 1985).

The sill variance represents the portion of the total semivariance that comprises spatial autocorrelation. Sill variances of bulk density, depth of topsoil, pH and organic matter are close to zero, signifying low variability of within-field variation. The values of the sill variance for Bray P varied among the two layers with values of 25924 ppm and 8002 ppm for topsoil and subsoil, respectively.

The range expressed as distance, and can be interpreted as the diameter of the zone of influence, which represents the average maximum distance over which a soil property of the two samples is related. At a distance less than the range, measured properties of two samples become more alike with decreasing distance between them. Thus, the range provides estimate areas of similarity. The range of spatial correlation determined by modeling the experimental, isotropic variogram varies among soil properties. Results showed that Bray P and depth of topsoil have short ranges of spatial correlation indicating that spatially related variation occurs over short distances. Observations also showed that Bray P and depth of topsoil have spatial correlation at short distances.

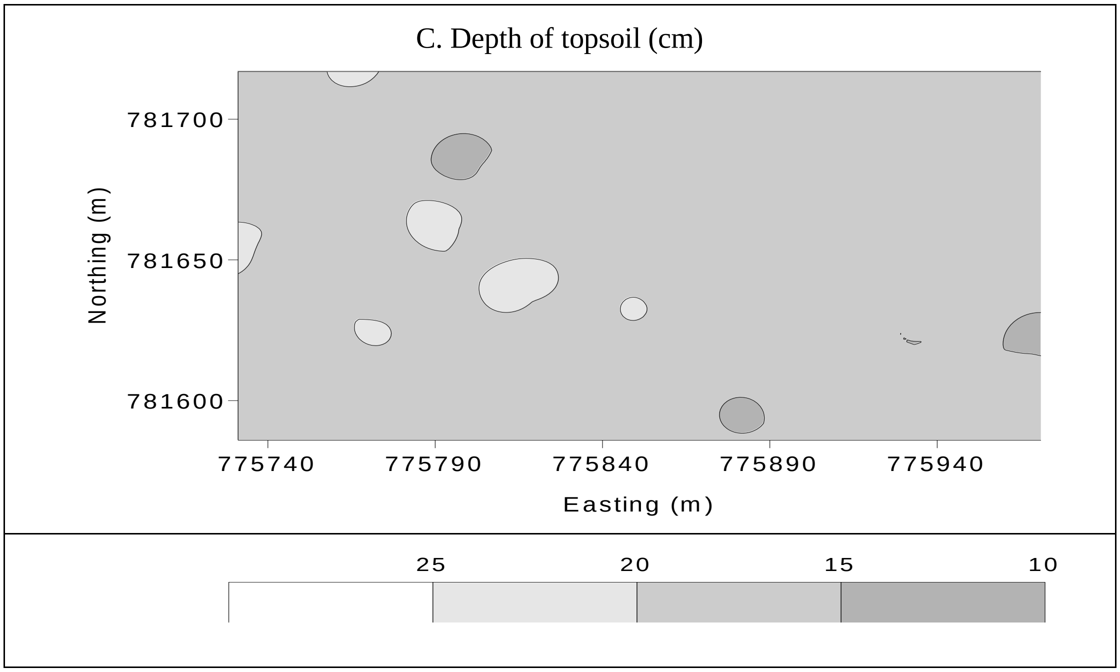
Soil pH displayed spatial correlation within a distance of 80 m and 77 m for both topsoil and subsoil, respectively, beyond which soil pH exhibited no significant spatial correlation. Soil organic matter exhibited the longest range of spatial correlation at the topsoil with values of 117m followed by bulk density (103 m) and total K (86 m).

The different ranges of spatial correlation of Bray P (20 m) and total K (86 m) of the topsoil may be related to the mobility of these soil nutrients. Soil P is extremely immobile in the soil, whereas, soil K has limited movement in the soil. Immobile nutrients indicate a short range of spatial correlation as shown by Bray P while soil nutrient with limited movement is illustrated by total K which was spatially correlated at longer distance. Several other studies have reported similar big differences between ranges of different soil variables trying to map soil variation at a field scale (Robertson et al., 1997; Bocchi et al., 2000; López-Granados et al., 2002). Results also showed that soil properties vary geographically due to differences in management history, climate, fertilization and other factors.

The spatial ratio (SR) was used to qualitatively define spatial dependence values, an indication of the degree of spatial variability. A spatial class ratio to define distinctive classes of spatial dependence was adopted from Cambardella et al. (1994). If the spatial class ratio was <25%, the variable was considered strongly spatially dependent; if the ratio was >25% and <75%, the variable was considered moderately spatially dependent; and if the ratio was >75%, the variable was considered weakly spatially dependent. A strong spatial dependence indicates low spatial variability while weak spatial dependence indicates high spatial variability.

The resulting variograms indicated the existence of weak to strong spatial dependence for all soil properties. Soil pH and total K were

Figure 3. Spatial variability map on soil depth of the study site



moderate on both soil depths, demonstrating moderate spatial variability. Spatial dependence appears weak for Bray P of the topsoil indicating a high spatial variability. Pronounced spatial variability is demonstrated for bulk density and organic matter of the topsoil and depth of topsoil, illustrating a low spatial variability.

Spatial variability maps

Depth of topsoil is 15-25 cm though the western part of the area had variable depths. (Figure 3). It has been classified as medium thick (10 - < 30 cm) based on the Australian Soil Classification. The productive capacity of a soil is generally related to topsoil depth. Depth of the topsoil (A horizon) is determined by the relative rates of accumulation and decomposition of organic matter. It is also related to the activity of soil fauna—earthworm and termite activity results in mixing of organic material at greater depths.

Available water capacity is a function of the depth of soil. The depth of the topsoil plays an important role in water holding capacity during dry spells and serves as the storage space for nutrients and anchoring of crop roots. Spatial variability in the depth of topsoil can explain at least some of the spatial variability in crop productivity.

Spatial variability maps of the topsoil and subsoil presented in Figure 4 revealed that the surface soil with a clay loam texture had a bulk density of 1.2 to 1.29 g cm^{-3}. The subsoil having a clay texture, differences in bulk density were observed in the southern part of the area where bulk density tends to increase with depth. This trend is caused by low organic matter in the area as shown in Figure 6.

For clay loam soils, bulk density less than 1.40 g cm^{-3} are suited for coconut cultivation. Subsoil bulk density may range from 1.2 to 1.5 g cm^{-3} for those soils exhibiting favorable tree growth (Craul, 1992). Soils with low bulk density are generally more suitable for agriculture, since the high pore space has a greater potential to store water and roots are able to grow more readily.

Figure 4. Spatial variability map on soil bulk density of the study site

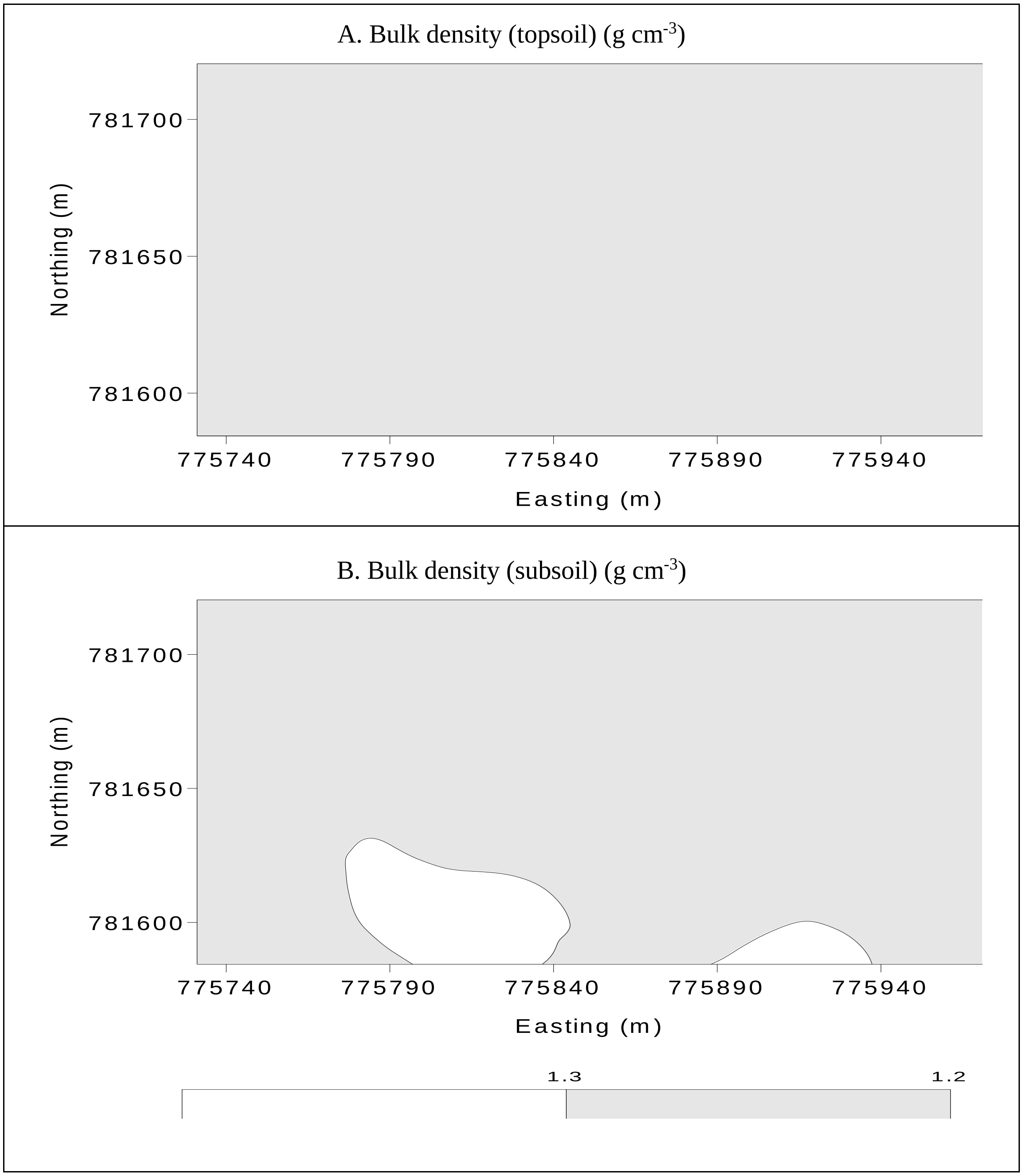
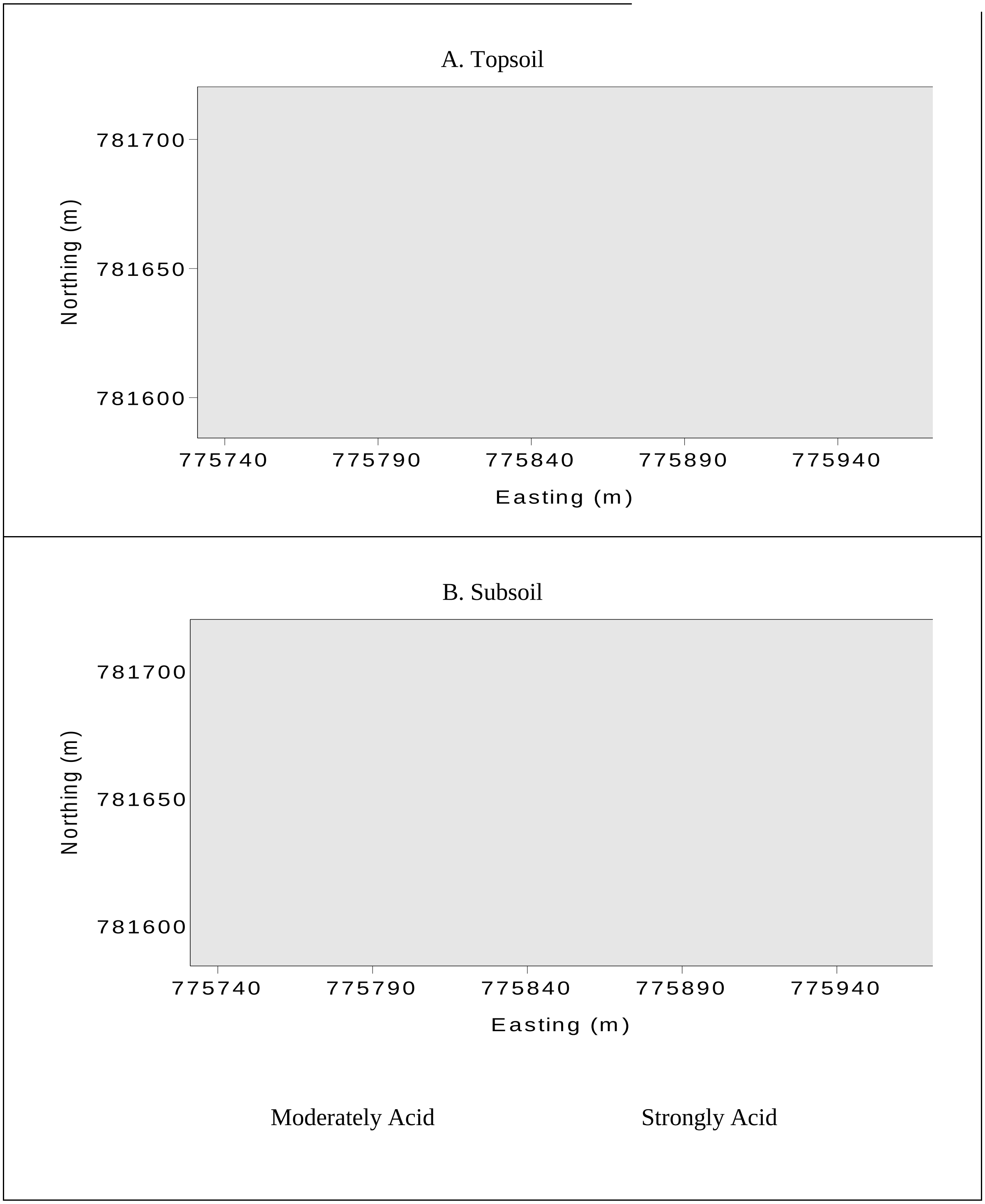
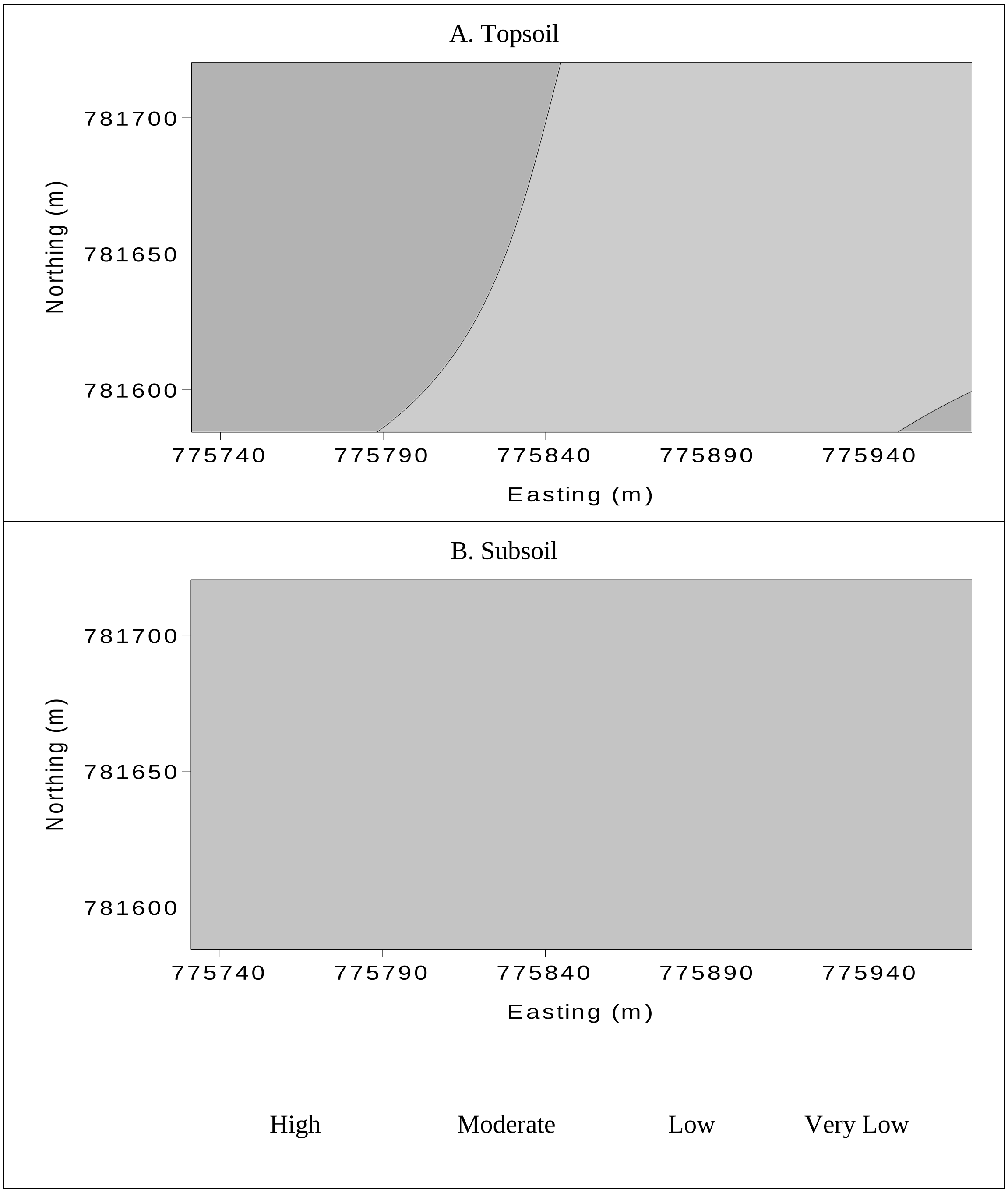


Figure 5. Spatial variability maps on soil pH of

Figure 6. Spatial variability maps on soil organic





Bulk densities that limit plant growth vary for soils of different textural classes. However, the bulk density of the A horizon of mineral soils is usually between 1.0 and 1.6 g cm^{-3}, root penetration is severely impacted at bulk densities greater than 1.6 g cm^{-3}. As a general rule the finer-textured soils like clay loams have more pore spaces and lower bulk densities than sandy soils. As density increases, pore space decreases and the amount of air and water held in the soil also decreases.

The degree of compactness which requires tillage for a given soil type is not well understood. However, there was no general accepted rule of thumb that exists which states that a certain bulk density limits plant productivity. However, some studies have been conducted in predicting detrimental effects to plant growth. Bowen (1981) suggested a general rule (with many exceptions) that bulk density measurements of 1.55, 1.65, 1.80 and 1.85 g cm^{-3} can impede root growth and thus will reduce crop yields on clay loams, silt loams, fine sandy loams, and loamy fine sands, respectively. Bulk density greater than 1.2 g cm^{-3} for clay soil, 1.6 g cm^{-3} for loam soil, and 1.8 g $cm^{-3}$for sandy loam adversely affected the root growth of rice (Kar et al., 1976).

Spatial variability maps of the topsoil and subsoil illustrated strong acidity (Figure 5), which is an indication of long term use of ammonium sulfate as one of the recommended fertilizers for coconut. Soils in the range 5.6 to 6.0 are moderately acid and below 5.5 are strongly acid. Most soils have pH values between 4.0 and 8.0. Fertilizers containing sulfur and nitrogen tend to lower the soil pH at the rate that often produces a noticeable effect within a few years. The most universal effect of pH in plant growth is related to nutrient absorption. Usually the optimum pH is between 6.0 and 7.5 because all plant nutrients are available. However, the ideal pH range for coconut is 5.5-6.5.

Spatial variability maps of organic matter content in Figure 6 showed a generally low (2.1-3.5%) organic matter content of the topsoil and very low (0-2%) in the subsoil though the area is covered with tropical kudzu. Further, the western part of the area had very low organic matter content in the topsoil. The soil organic matter content is most concentrated in the topsoil.

Most of the soils contain 1-6% organic matter (Thompson and Troeh, 1978). More decomposition occurs in the topsoil because more organic matter is added in this zone. The organic matter content of any horizon depends partly on how much is turned over into the soil every year and partly on what percentage of the organic matter decomposes during the year. Organic matter is constantly undergoing change and must be replenished continuously to maintain soil productivity. Chemically, organic matter is the reservoir of nitrogen and phosphorus.

In Figure 7, kriged maps revealed low Bray P in the topsoil and subsoil with variable distribution within the study area, however, the Bray P content of surface horizon is greater than that of the subsoil. The low availability of Bray P is controlled by the strong acidity (pH 4.5-5.5) of the soil following repeated application of ammonium sulfate fertilizers in the area.

Phosphorus nutrition is critical because the total supply of P in most soils is low. Reactions that reduce P availability occur in all ranges of soil pH but can be very pronounced in alkaline soils ($pH > 7.3$) and in acidic soils ($pH < 5.5$). In acid soils, phosphate is fixed by iron and aluminum. Aluminum is most active fixing phosphate at a pH of 5.0 to 5.5. As soils become more acidic (pH below 5), phosphorus is fixed in iron phosphates. Acid soils have low available P because the phosphate forms are not readily soluble and are not readily absorbed at the cation exchange sites of the soil. Phosphorus, on the other hand, is available to plants when soil pH is between 6.0 and 7.0.

Figure 7. Spatial variability maps on soil Bray phosphorus (ppm) of the study site

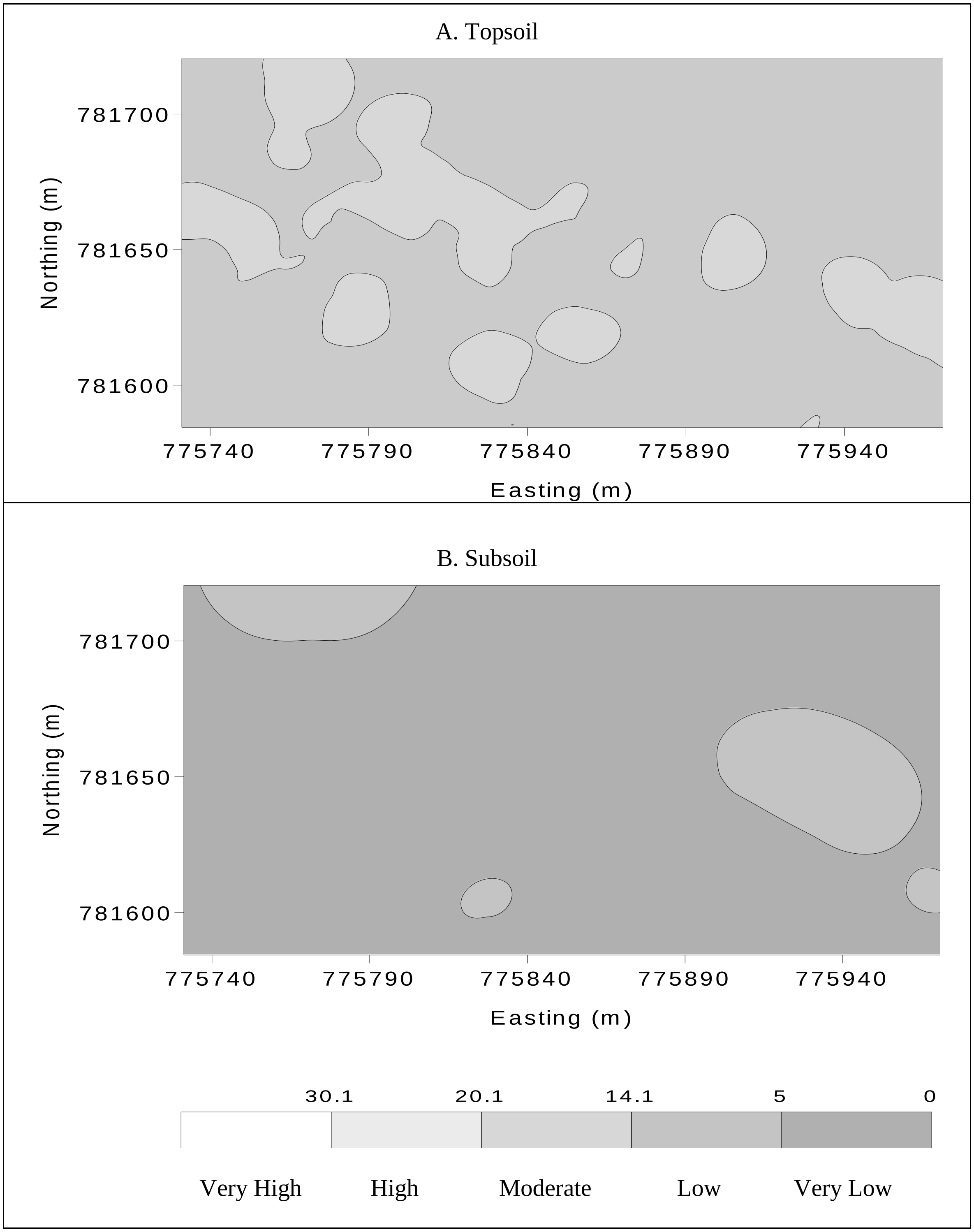
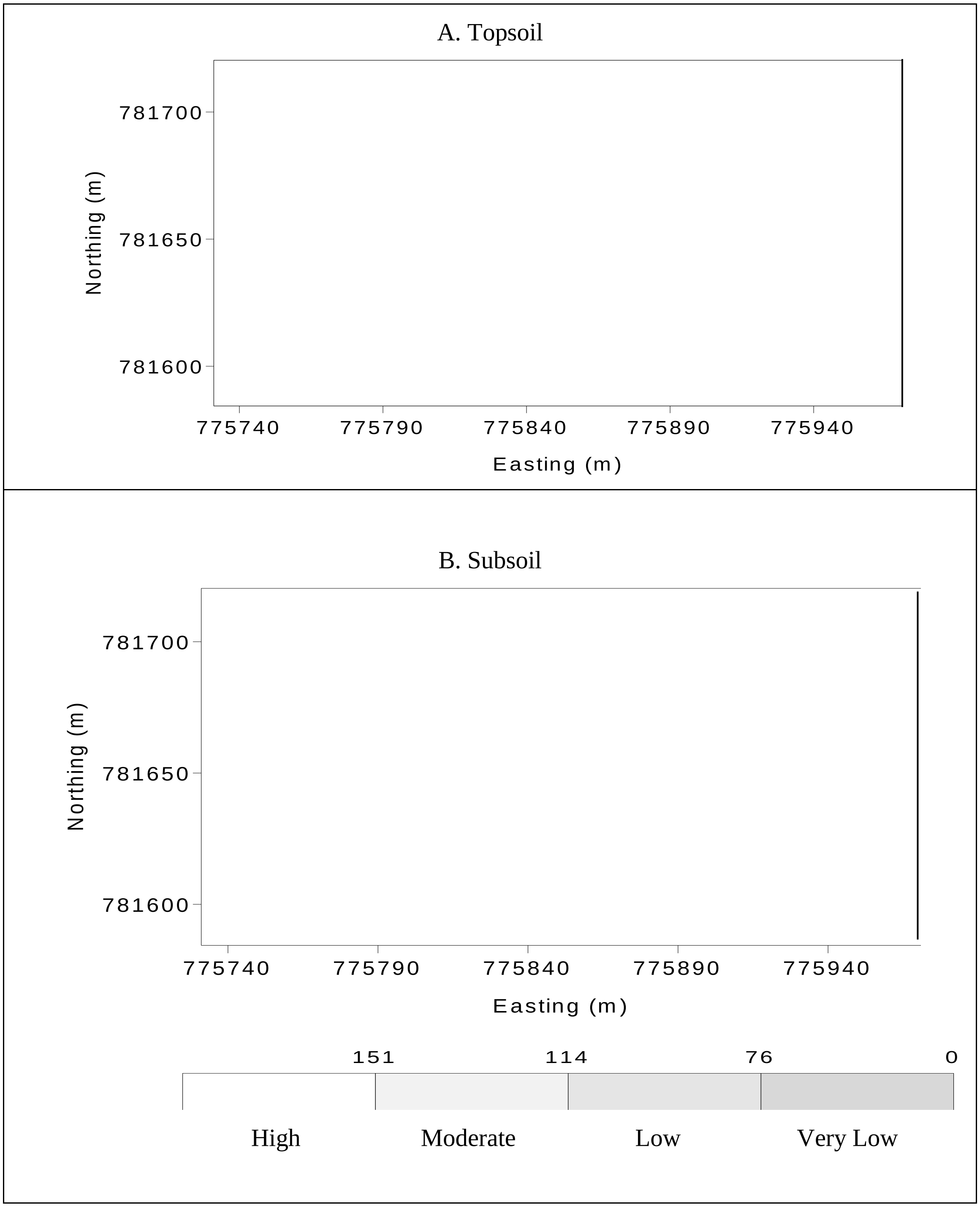


Figure 8. Spatial variability maps on soil total potassium (ppm) of the study site



Kriged contour maps in Figure 8 indicated a high total K in the topsoil and subsoil of the study site. Soil profiles in these areas were classified as Tugbok clay loam, which are comprised of volcanic soils containing large amounts of potassium required by the coconut.

Most mineral soils are comparatively high in total K. The original sources of K are the primary minerals such as the micas and the feldspars. However, most of the K is in the primary mineral and nonexchangeable forms.

Since clay soils develop from the decomposition of potassium-rich primary minerals, it follows that soils high in clay content have a relatively high K content.

Conclusion

Spatial variability maps showed that the area is generally strongly acidic, low in organic matter and Bray P but high in total K with low bulk density values (1.2 to 1.29 g cm^{-3}) and medium depth topsoil. These maps generated by kriging are expected to provide information in precision agriculture in order to make better management decisions, reduce chemical and fertilizer costs through more efficient application, provide more accurate farm records, improve crop yield, and reduce agro-chemical pollution. Precision agriculture relies on the existence of in-field variability.

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