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Assessing Soil Quality of a Regenerating Mangrove Forest Using Geospatial Modelling Approach

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ABSTRACT

Mangrove forest plays an important role in our ecosystems. The functions of mangroves include coastline protection, aquaculture, firewood source, charcoal production and the conservation of floral and faunal species. The decline in mangrove coastlines over the years has raised the need to investigate and document the soil quality of microsites within regenerating and established mangrove stands. This paper aims to showcase the important changes that took place in a newly regenerating mangrove using geospatial tools as a preliminary guideline on rehabilitating mangroves. An established mangrove stand (back portion) and a newly regenerating mangrove stand (front portion) were selected in the west coast of Peninsular Malaysia. Systematic sampling with 40 quadrants each measuring 5 m^2 were established in both plots. Soil sampling at 15 cm depths were carried out and geo-referenced using a GPS receiver. Electrical conductivity, soil pH and soil organic carbon (C) were analysed using standard laboratory practices. The variables were first explored using univariate statistics. This was followed by variography and kriging analyses to quantify spatial variability of soil variables. Soil variables exhibited a strong to moderate spatial dependence. Surface maps of the test variables displayed spatial clustering and acceptable accuracy of interpolated values. Values for soil C and soil EC were significantly lower and soil pH was near neutral in the regenerating site but the continuous improvement of soil structure and vegetative proliferation may promise a successful rehabilitation model of coastline mangroves in time. Site-specific management of mangrove forest based on soil quality is necessary for future rehabilitation initiatives that incorporate selection of suitable species for planting, application of soil amendments and innovative planting methods to boost survival of seedlings.

Keywords: **Coastline ecosystem, spatial variability, soil carbon, soil pH, soil electrical conductivity, rehabilitation**

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INTRODUCTION

The term mangrove is used to describe a group of floristically diverse trees and shrubs which characterise the intertidal vegetation of many tropical and subtropical areas. Mangroves are an integral part of the ecosystem serving various functions such as coastline protection, impeding salt water intrusion, aquaculture, fodder for pole, firewood, charcoal production and conserving floral and faunal species (Walter *et al.* 2008; Spalding 2004). However, this unique ecosystem is under tremendous stress due to erosion, excessive anthropogenic activities and natural disasters such as a tsunami. The coastlines of Malaysia have witnessed drastic decline in recent years with 29% of the Malaysian coastal areas being reported to be vulnerable to serious erosion (Wan Rasidah *et al.* 2015).

Most mangroves species are influenced by soil salinity and soil pH which affect survival, adaptation and growth. Electrical conductivity (EC) has been widely used in agriculture and forestry to describe within-field spatial variability in some soil properties (Lund *et al*. 1999; Shaner *et al.* 2008), and is considered a rapid, easy, reliable, and cheap method for mapping within field heterogeneity in soil properties (Mondal *et al.* 2011). As a strong relationship exists between soil properties and soil EC (Kitchen *et al*. 2003; Sudduth *et al*. 2005), variability in soil biophysical characters such as soil texture, organic matter, soil moisture, soil temperature and cation exchange capacity can affect soil EC readings.

Soil pH measurement is useful because it is a predictor of various chemical activities within the soil. Soil pH significantly affects plant growth and species, primarily due to the change in availability of essential elements such as phosphorus (P), as well as non-essential elements such as aluminium (Al) that can be toxic to plants at elevated concentrations (Joshi and Goshe, 2003. The importance of both soil salinity and pH for the growth of mangroves has been emphasised by Wakushima *et al.* (1994) and Joshi and Goshe (2003) whereby distribution of mangrove species differs with varying levels of pH and EC. This serves as a useful tool in making management decisions concerning the type of plants suitable for which location and the amount of soil amelioration needed to enhance growth. Litter is abundant in mangroves, being derived primarily from leaves, twigs, bark and dead roots. They cover the soil surface and slowly decompose to form organic matter that increases microbial biomass and supports nutrient transfer. Soil organic matter (C), may control soil quality which determines the sustainability and productivity of soils (Swezey *et al*. 1998) of mangroves and its abundance or absence alters the soil health dynamics.

Precision Agriculture is a tool that has been widely used in recent times both in developed and the developing nations. Its purpose is to build a farming management system, with the capability of expanding area profitability by taking into account precise data about spatial variability in natural traits that can possibly cause yield variety (Mondal *et al*. 2011). It is quick, easy and efficient. The implementation of precision agriculture requires the adoption of spatial technologies such as global positioning system (GPS), geographic information system (GIS) and remote sensing mapping. This is also the case with precision forestry which utilises similar concepts for forest management. Precision forestry is defined by Taylor *et al*. (2002), as planning and conducting site-specific forest management activities and operations to improve wood product quality and utilisation, reduce waste, increase profits and maintain the quality of the environment. Precision forestry provides real time data on variability maps, in terms of tree growth, tree nutrition and harvest. Spatial variability occurs when a quantity that is measured at different spatial locations exhibits values that differ across the locations. Spatial variability can be assessed using spatial descriptive statistics such as range. Precision forestry or site-specific management is aimed at managing soil spatial variability by applying inputs in accordance with the site-specific requirements of a specific soil and tree (Mzuku *et al.* 2005) in order to save cost, time and labour.

The aim of our study was to detect and compare spatial variability of soil pH, soil salinity (EC) and soil carbon of a regenerating and an established mangrove belt using geostatistical tools.

Since concerted on-going efforts are being carried out in order to rehabilitate the mangrove belts on the West Coast of Peninsular Malaysia, we hope that the results can indicate the soil status that can be further utilised by forest managers in deciding on management strategies such as species selection, soil ameliorations and innovative planting techniques that will assure the survival of introduced mangrove seedlings via the rehabilitation efforts.

MATERIALS AND METHODS

The mangrove forest in Sungai Haji Dorani, Sungai Besar Selangor (3° 38'N, 101° 01'E) is mainly dominated by the *Avicennia* and *Rhizophora* species. The annual average temperature here is about 26.9 °C, with the highest being in October (27.7 °C) and the lowest being in July (26.2 °C). Annual rainfall and relative humidity are approximately 130 mm and 70–95%, respectively (Jeyanny *et al.* 2009). In 2007, 4 units of geotubes measuring 50 m each were installed as a wave breaker to impede the effects of erosion and the impact of waves on the mangrove coastline. By 2016, the installation of geotubes allowed the regeneration of mangrove forests overlooking the sea. An established mangrove stand (back portion) and a newly regenerating mangrove stand (front portion) were selected for comparison. The range for diameter at breast height (DBH) for the newly regenerating mangrove stand ranged from 3.7 – 10.3 cm whereas the values for established mangrove stands, the DBH ranged from 2.8 – 11.5 cm, respectively. Plots of 5 x 5 m quadrants with 40 quadrants each were established for both mangrove stands. The length and width of systematic sampling for each block (i.e. mangrove type) was 25 m x 20 m, respectively. Thus, the total sampling area for each block was 0.05 ha. Soil samples were collected at 0-15 cm depth in each quadrant and transported to FRIM for the determination of soil pH (Crison micro pH 2001, Crison Instruments, Spain), electrical conductivity (Mettler-Toledo Seven Easy, Mettler Toledo, Switzerland) and soil organic carbon using Walkley and Black method. Soil pH, soil EC and soil C were analysed using T-test and the mean comparison computed using Duncan Multiple Range Test (DMRT) in Statistical Analysis System (SAS). The variables were also subjected to descriptive statistics, normality check and non-spatial outlier detection in Statistix version 8.1. Spatial analyses for variables were carried out using variography and interpolation techniques (Balasundram *et al.* 2008). The variogram is a tool that quantifies spatial correlation. Variography and kriging were computed using GS+ 7.0 (2004). Measured and kriged values were mapped using Surfer 11 (2012). Spatial dependence of the data was computed using the nugget to sill ratio according to Cambardella *et al.* (1994) as shown in Table 1.

TABLE 1
Classification of spatial dependence

Ratio	Inference
Nugget:Sill< 0.25	Strong spatial dependence
0.25 <Nugget:Sill<0.75	Moderate spatial dependence
Nugget: Sill>0.75	Weak spatial dependence

Kriged values were cross-validated to assess accuracy of the interpolated values using the following three accuracy measurements procedure.

First, the interpolated Mean Error (ME) should be close to zero and is calculated as follows:

$$ME = \frac{1}{n}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)] \qquad (i)$$

where

n = the number of sample points
(z ̅) = is the predicted value of the variable at point x_i and
z(x_i) = is the measured value of the variable at point x_i

Second, the Mean Squared Error (MSE) should be less than the sample variance. The MSE is given by

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)]^{2} \qquad (ii)$$

Third, the ratio of the theoretical and calculated variance, called the Standardized Mean Squared Error (SMSE), should be approximately close to one. The SMSE is given by:

$$SMSE = \frac{\frac{1}{n-1}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)]^2}{\sigma^2} \qquad (iii)$$

where σ^2 is the theoretical variance.

RESULTS AND DISCUSSION

Our results showed that the amount of soil carbon in the established mangroves was 47% significantly higher compared to the regenerating mangroves (Table 2). The soil pH for the established site was at least 1 unit lower compared to the newly regenerating area which recorded near neutral (pH 7) values. The salinity of the established mangroves were 1.7 fold significantly higher compared with the newly regenerating mangroves. This study showed that the established mangroves had slightly higher C content (organic matter) compared to a well-established mangrove forest (2.64%) in the Kelantan Delta (Jeyanny and Wan Rasidah, 2015). Soil pH at 6.5 to 7.0 is considered ideal as it directly increases the solubility of the plant nutrients in soil solutions (Brady and Weil 2008). The higher EC values in the established area indicate the tolerance of mangrove species and its adaptability to grow well as Avicennia were reported to withstand EC levels up to 39 ms/cm (Chan and Baba 2009).

TABLE 2
Total soil C, soil pH and soil EC of the study site

Variables	Regenerating mangrove	Established mangrove
C (%)	2.45a**	3.62b**
	0.05¥	0.14
pH	7.63a**	6.59b**
	0.02	0.04
EC (ms/cm)	11.99a**	20.92b**
	0.26	0.86

*¥ : Standard error * significant at $p< 0.05$; ** significant at $p< 0.01$*

Soil pH and soil salinity (EC) values for the regenerating site (front) concurred with a previous study carried out by Mohamad Fakhri *et al.* (2017) in the mudflats. Previous reports in the mudflats have shown that severe soil degradation, soil erosion, structureless substrates and soil depletion (Jeyanny and Wan Rasidah, 2015; Jeyanny *et al.* 2009) have occurred. However, with geotubes placement, it was observed that the area cordoned off for restoration have transitioned from bare mudflats to newly regenerating vegetation.

For the regenerating site, all the variables were normally distributed (Table 3). The mean for soil pH was at the neutral zone. All the variables displayed negative skewness except for soil C. Negative kurtosis was displayed by the variables C and EC, implying a rather flat frequency distribution. The coefficient of variance (CV) was 1.35% for soil pH and 13.47% for soil EC. A slight degree of variation was detected in the test variables inferring minimal variability for test variables.

For the established site, all the variables were normally distributed (Table 3). The mean for soil pH was acidic. Soil pH and EC at the back portion displayed negative skewness. Only soil pH displayed negative kurtosis, showing variable frequency distribution. CV was 4.67% for soil pH and 25.61% for soil EC.

TABLE 3
Descriptive statistics of parameters at study site

Parameters	n[1]	Mean	Median	CV(%)	Skewness[2]	Kurtosis[2]	Normality[3]
Regenerating mangrove							
C	37	2.45	2.39	12.40	0.25	-0.12	0.21
pH	37	7.63	7.63	1.35	-0.67	0.10	0.12
EC	38	11.99	12.08	13.47	-0.006	-0.40	0.10
Established mangrove							
C	39	3.62	3.67	24.94	0.25	0.67	0.52
pH	40	6.60	6.67	4.67	-0.68	-0.23	0.07
EC	39	20.92	21.40	25.61	-0.89	1.43	0.06

CV: Coefficient of Variation

For the regenerating site, almost all variables fitted the cross-validation assumptions (Table 4). The SMSE values for C were slightly lower than 1 but were acceptable. The SMSE for soil pH at the established mangrove did not fit the criteria, implying that the cross-validation assumption was poorly recognised. However, ME and MSE were acceptable (Table 4). This could be due to the very small range of distribution for soil pH at the back portion that gave a CV of 4.6%, implying that soil pH did not vary greatly.

For the regenerating site, the semi-vari 0 grams corresponding to soil C, EC and pH were constructed with the active lag distance of 51 m, but the uniform interval was set within the range of 5.1 – 9 m [Figures 1(a)-(c)]. For soil C, the best model was spherical, whereas pH and EC displayed exponential models [Figures 1(a)-(c)]. The semi-variance value at the shortest distance is defined as the sill. The nugget shows the analytical error while the sill expresses the amount of spatial structural variance (Liu *et al*. 2010). Spatial dependence was calculated

TABLE 4
Cross validation statistics of kriged values at study site

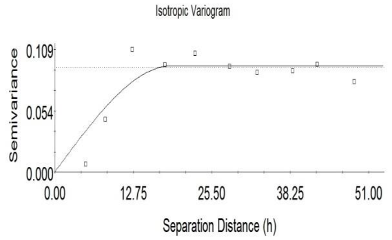
Parameters	Model	Sample variance, σ^2	ME	MSE	SMSE
Regenerating mangrove					
C	Spherical	0.09	0.004	0.05	0.60
pH	Exponential	0.01	-0.001	0.01	1.08
EC	Exponential	2.61	-0.003	2.60	1.02
Established mangrove					
C	Exponential	0.81	-0.00	0.83	1.05
pH	Spherical	0.09	0.005	0.04	0.44
EC	Exponential	28.71	0.14	23.94	0.86

ME: Mean Error; MSE: Mean Squared Error; SMSE: Sum of Mean Squared Error;
ME = 0; MSE ≤ σ^2; SMSE = 1

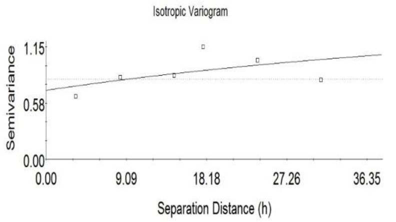
by dividing nugget with sill and was found to range from <0 to 0.5. Strong spatial dependence was shown by soil C, while all other variables displayed moderate spatial dependence [Figures 1(a)-(c)]. The effective range (ER) values were moderate to distant, 19 to 632 m. Sampling points which are distanced greater than the ER is spatially independent, and will no longer demonstrate spatial correlation (Balasundram *et al.* 2008).

For the established mangrove, the active lag distance was computed at 36.35 whereas the uniform interval was set within the range of 3.64 – 7.5 [Figures 1(d)-(f)]. Soil pH and EC displayed a spherical model whereas soil C displayed an exponential model. Soil EC had the highest nugget and sill value, 18.77 and 39.88 respectively. Strong spatial dependence was shown by soil pH, whereas C and EC showed moderate spatial dependence. The longest ER was shown by C (158.3 m) and shortest by pH (75.0 m) [Figures 1(d)-(f)]. Soil C is known to have longer ER (Jeyanny *et al*. 2016; Law *et al*. 2009) due to the large spatial variations in soil C (Zhang and McGrath 2004).

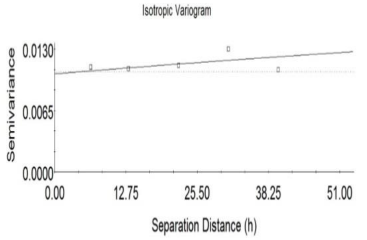
The distribution and trends of both measured and kriged values for each variable are represented as surface maps in Figures 2. Almost all variables exhibited spatial clustering of test values. For soil C, the north-west direction had the highest amount of C, gradually reducing towards the south-west direction [Figure 2(a)] the regenerating mangrove. The soil pH at the north-west region at the regenerating mangrove showed the highest values but reached a plateau at the south-west region [Figure 2(b)]. We believe that the amount of soil C accumulation was more profound in the north-west region due to the swirling effects of wave action that may have deposited organic rich sediments at this area that assisted in the soil aggregation processes. The increase in soil pH at



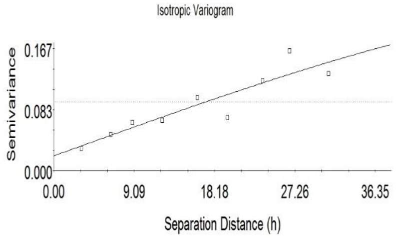
a) Total Carbon (%), Regenerating mangrove
Model: Spherical; Spatial dependence:Strong; Nugget: 0.0001; Sill: 0.09; ER: 19.0 m



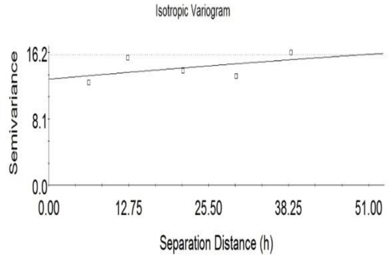
d) Total Carbon (%), Established mangrove
Model: Exponential; Spatial dependence: Moderate; Nugget: 0.70; Sill: 1.4; ER: 158.3 m



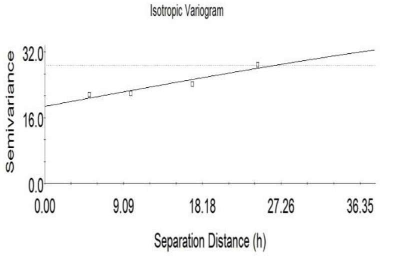
b) Soil pH, Regenerating mangrove
Model: Exponential; Spatial dependence: Moderate; Nugget: 0.01; Sill: 0.02; ER:632.7 m



e) Soil pH, Established mangrove
Model: Spherical; Spatial dependence: Strong; Nugget: 0.02; Sill: 0.23; ER: 75.0 m



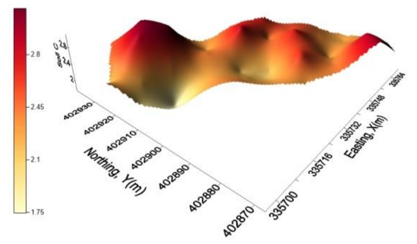
c) Electrical Conductivity, Regenerating mangrove
Model: Exponential; Spatial dependence: Moderate; Nugget: 2.24; Sill: 4.48; ER: 616.8 m



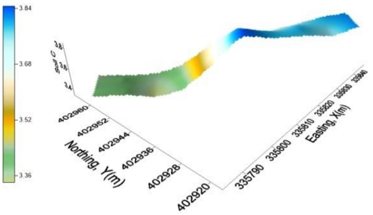
f)Electrical Conductivity, Established mangrove
Model: Spherical; Spatial dependence: Moderate; Nugget: 18.77; Sill: 39.88; ER: 81.0 m

Figures 1 (a-f): Spatial structure and attributes of selected soil variables at the regenerating and established mangroves in Sungai Haji Dorani, Sungai Besar

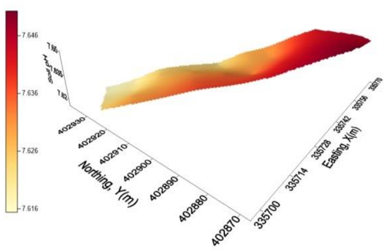
this location was due to the dynamic water percolation and seawater intrusion (Jeyanny *et al.* 2018), which is more neutral compared to the coastal belt. Soil EC at the south-western area displayed the highest values whereas values dipped towards the north-west boundary [Figure 2(c)] for the same site. There is a clear indication that the relationship between soil pH and soil EC is antagonistic in this area and it may be correlated with other soil chemical properties which are not described here.



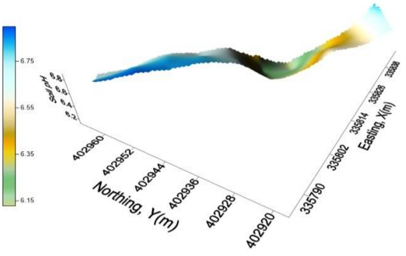
a) Total Carbon (%), Regenerating mangrove



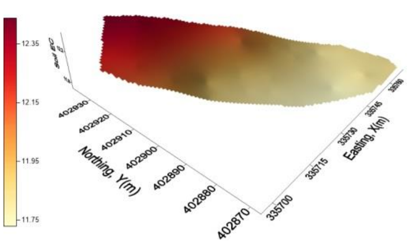
d) Total Carbon (%), Established mangrove



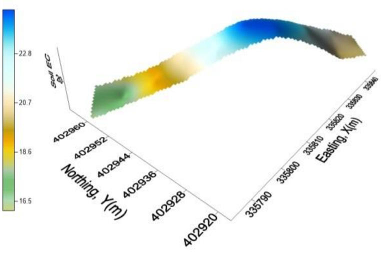
b) Soil pH, Regenerating mangrove



e) Soil pH, Established mangrove



c) Electrical Conductivity, Regenerating mangrove



f) Electrical Conductivity, Established mangrove

Figures 2 (a-f): Spatial variability of selected soil variables (based on measured and kriged values) at the regenerating and established mangroves in Sungai Haji Dorani, Sungai Besar.

Soil C surged in the eastern region but levelled off towards the west [Figure 2(d)] at the established mangroves. Soil pH at the western side had the highest values but took a dip towards the east [Figure 2(e)]. Our observations at site show that the mangrove belt is close to outlets that transport residues from agricultural and human activities in the east. This may have affected the surge in soil C and acidic conditions although these assumptions need further investigations. Electrical conductivity has the highest values around the north-east region and the lowest values around the south-west region, indicative of the abundant *Avicennia* trees which are more tolerant to higher EC levels (Chan and Baba 2009) [Figure 2 (f)].

CONCLUSION

Soil total C, soil pH and soil EC exhibited spatial variability in the established and regenerating mangroves. Spatial structure of test variables varied and mostly fitted spherical or exponential models. Variables exhibited a strong to moderate spatial dependence. The established mangrove showed shorter ER, implying that spacing of samples should be closer in the established mangroves. The majority of surface maps of the test variables showed distinct spatial clustering and displayed acceptable accuracy of interpolated values, suggesting that total C, soil pH and soil salinity can be estimated reliably via geo-spatial analysis. Although we acknowledge that coastal mangroves are dynamic and constantly changing, this study was able to elucidate the varying soil qualities of an established and a newly regenerating mangrove forest using spatial maps. The gradual increase in soil properties (soil C and EC) in the regenerating mangroves may indicate the capacity of soils in decomposition and nutrient cycling processes in supporting the evolving mudflat zone for vegetative productivity. Soil restoration with wave breakers may benefit the degrading coastline in the long run, provided that the soil environment is conducive for mangrove forest re-establishment. These maps can be utilised by forestry managers in understanding the natural evolving environment of the mudflats as well as managing the area site-specifically for future rehabilitation strategies and monitoring of coastal mangroves. Since most rehabilitation strategies are labour and cost intensive, a rapid assessment of the coastline using geospatial tools will provide baseline data that can be utilised for suitable planting techniques (i.e. soil ameliorations, species selection) and further monitored for spatial and temporal changes.

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