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Spatial Variability of Soil Inorganic N in a Mature Oil Palm Plantation in Sabah, Malaysia

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Abstract: The identification and understanding of soil factors influencing yield variability of oil palm enable their efficient management. Soil samples were therefore collected from a fertilizer response trial on oil palm to study the spatial inorganic N distribution and some selected soil chemical properties as affected by long-term N fertilizer applications. The experiment was conducted on mature oil palms grown on Kumansi family (Typic Paleudults) soil in Tawau, Sabah, Malaysia. The soil samples were taken from 2 areas; with and without N treatments for 8 years. They were analyzed for total N, NH_4^+-N, NO_3^--N, exchangeable K, and pH. Semivariance analysis was used to characterize the spatial variance of soil NH_4^+-N and NO_3^--N while point kriging method was used to illustrate their spatial distributions. Results showed that application of N in the palm circle increased soil NH_4^+-N above 150 mg kg^{-1} at 0 to 15 cm depth. In unmanured plot, the NH_4^+-N contents were similar in the different sites within a palm area although the frond heap area tended to have higher NH_4^+-N probably due to the N return from the decaying cut fronds. The coefficient of variations for both soil NH_4^+-N and NO_3^--N exceeded 30% even within each microsite of palm circle, interrow, frond heaps, and harvesting path. Semivariance analysis showed that the maximum range of soil NH_4^+-N could be reached at 10 m and 90 m in areas with and without N respectively, indicating that the application of N fertilizer reduced its spatial variability in mature oil palm agroecosystem. The kriged soil map showed localized spots of high NH_4^+-N content, which corresponded to the palm circles where N fertilizer was applied. Gradual changes in soil fertility were observed in area without N, moving from northern to southern portion of the field. Long-term applications of N caused significant downward movement of NH_4^+-N and NO_3^--N to the lower soil depth. They also decreased the soil pH from 4.2 to 3.7, and caused leaching of K to the lower depth. Fertilizer should be broadcast in the interrow in mature oil palm agroecosystem to reduce spatial N variation and other detrimental effects.

Key words: Spatial variability, soil exchangeable ammonium, soil available nitrate, soil inorganic nitrogen, oil palm, Malaysia

INTRODUCTION

Uniformity trials on a wide range of soils indicate that the coefficient of variations (CV) of fresh fruit bunch (ffb) yield commonly ranges between 30 and 60%[1,2,3]. Part of the yield variability could be attributed to soil heterogeneity, the Fairfield Smith's b, which commonly ranges from 0.4 to 1.0 (2). Similarly, Ng and Ratnasingam[4] and Law and Tan[5] obtained high variation in soil fertility even within the same soil series in Peninsular Malaysia, particularly for soil organic C and N. Goh *et al.*[6] reported that the CVs for soil chemical properties in Sabah could exceed 100% within the same soil series.

Apart from the above, significant soil variation can arise from land use and management practices[7,8]. High spatial variability of soil fertility was also found within microsites of palm circle, frond heap and interrow within single palm areas due to previous fertilizer application practices[8], which might affect palm growth

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and the reported spatial variation of ffb yields. In fact, Goh *et al*.[9] showed that about 75% of the ffb yield variation was spatially correlated and it could be managed provided the causal factors can be identified. Thus, an understanding of the nature and magnitude of these variabilities in the field is necessary for efficient and effective management of the fields[10]. This study was conducted to investigate the spatial distribution and variability of soil inorganic N as influenced by long term N fertilizer management.

MATERIALS AND METHODS

The study site was located in a fertilizer response trial conducted by Applied Agricultural Research Sdn. Bhd. at Sri Kunak Estate, Tawau, Sabah, Malaysia. The trial was a 3×3×2 factorial combination of NPK arranged in a randomized complete block design (RCBD) with 3 replications. The oil palms were planted in 1982 in a triangular pattern with a planting distance of 9.1 m×9.1 m×9.1 m. The area with frond heaps and harversters' path alternated between palm rows Fig. 1. Each tree has an approximate 2 m radius of clean weeded area around the palm base, called the palm circle. Ammonium chloride and muriate of potash were applied in 2 split applications and spread within the palm circles each year. Jordan phosphate rock was applied once a year in the interrow.

Two clusters of palms were selected for the study. The oil palms in the first cluster have been fertilized with N at 1.75kg N palm^{-1} year^{-1} or 242 kg N ha^{-1} year^{-1}

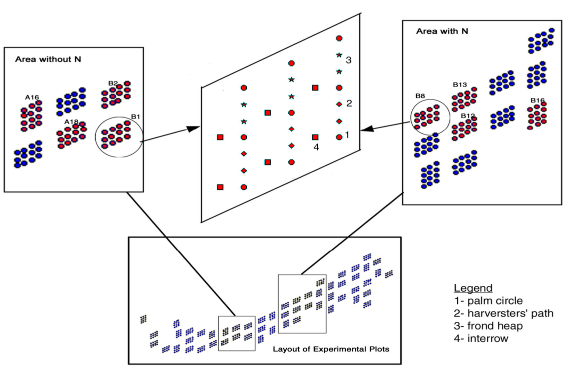

Fig. 1: Diagrammatic representation of experimental site

since 1992 when they were 10 years old. The other cluster of oil palms has not been fertilized with N for the past 10 years, i.e. since 1992. Each cluster consisted of 4 plots of 12 palms, that is, 48 palms per treatment. These plots were physically close to each other within the field Fig. 1. Point map of the individual palms for both treatments showing their relative positions in the field was geocoded using non-earth projection system in meter unit. The total area covered was 160 m×90 m for N treated plots and 120 m×115 m for the control plots without N application.

Soil sampling was carried after demarcating each palm area into 4 microsites; frond heap, palm circle, interrow, and harversters' path, respectively as shown in Fig. 1. A proportion of 8:4:4:4 random soil samples at 2 depths of 0-15 cm (first depth) and 15-30 cm (second depth) were collected from the frond heap, palm circle, interrow and harversters' path respectively with a core auger. The proportion used in the sampling followed the estimated area of each microsite. The soil samples were then bulked for each microsite. The soils were air-dried, ground and sieved to a 2 mm sieve and stored in plastic containers. The soil samples collected from the first depth were analyzed for soil inorganic-N (NH_4^+-N and NO_3^--N) which were extracted by shaking with 2 M KCl at 1:10 (soil: solution) for 2 hours. The soil KCl-suspension was filtered using Whatman No. 42 filter paper. NH_4^+-N and NO_3^--N were then determined by steam distillation using MgO and Devardas' alloy[11]. Three random soil samples at both depths were then selected from the palm circle of each plot to study the influence of N fertilizer on soil pH, exchangeable potassium, total N, NH_4^+-N, and NO_3^--N. Soil pH was determined by using a pH meter in a 1:2.5 soil: water suspension. Potassium was extracted from the soil using 1 N NH_4OAc (pH 7.0) solution[12] and determined using atomic absorption spectrophotometer. Total N was analysed using the Kjeldahl procedure[13].

The data between the microsites failed the Maunchly Sphericity test and therefore, violated the two assumptions of classical univariate ANOVA, namely, the independence of adjacent samples and the homogenity of variance[14]. Thus, the effects of manuring on soil inorganic N at each microsite were examined using the repeated measures in space analysis, a modified univariate F-test[15,16]. Pearson correlation coefficient was calculated to test for correlation between selected soil chemical properties at the first and second depths. All univariate statistical tests were performed using Statistical Analysis System[17]. The geostatistical analysis, semivariogram[18] and kriging[19], was carried out using GS+™, Gamma Design Software. The active lag distance for the grid in both fields was limited to 80% of the maximum field range. The lag interval in the semivariogram was fixed at 9.1 m based on the planting distance of oil palm. Selection of the models for the semivariogram was based on the Akaike Information Criterion (AIC) as described by Webster and McBratney[20]. The spatial soil maps were constructed by first using the point kriging method to estimate soil NH_4^+-N at unsampled locations and then clustering them into 5 soil classes of 25 mg kg^{-1} equal contour intervals. To avoid irregular field shape boundary and for comparing among plots with and without N, a rectangular field boundary of 165 m width and 120 m long was selected.

RESULTS AND DISCUSSION

Variation among Microsites: The components of variance calculated from the repeated measures analysis of variance (ANOVA) is shown in Table 1. The statistical analysis demonstrated high heterogeneity of soil NH_4^+-N between and within the plots at the first depth of 0-15 cm. Similar results were obtained for NO_3^--N. The significant variations of soil inorganic N particularly among the plots without N treatment might have come from planting practices before commencement of the trial or inherent soil N status.

Higher concentrations of NH_4^+-N (>150 mg kg^{-1}) were found in the palm circles where fertilizer was applied Fig. 2. The distinctly higher concentration of NH_4^+-N in the palm circle compared with the other neighbouring microsites indicated that lateral movement of NH_4^+-N was probably minimal in the experimental site. This could be due to the relatively gentle slopes (< 8°) and moderate annual rainfall of less than 1900 mm. The results also concurred with an on-going erosion study in the same estate on similar soil type where average annual run-off losses were low and below 22%[21].

The NH_4^+-N content was significantly higher in the frond heap compared to other microsites in areas without N application (Fig. 2). This suggests that the frond heap is an important source of mineral N for N-deficient oil palms.

Table 1: Components of variations of soil inorganic-N (NH_4^+-N and NO_3^--N) in an oil palm plantation

	df	Mean Square	F Test
a. NH_4^+-N			
Intercept	1	660928.2	1648.9*
Plot	3	2634.6	6.6*
Treatment	1	88649.8	221.2*
Error	91	400.8	
Microsites	3	98770.6	223.9*
Microsites*Plot	9	3228.4	7.3*
Microsites*Treatment	3	118728.1	269.1*
Error	273	441.2	
Total	383		
b. NO_3^--N			
Intercept	1	21538.2	497.4*
Plot	3	312.5	7.2*
Treatment	1	845.8	19.5*
Error	91	43.3	
Microsites	3	56.5	1.6ns
Microsites*Plot	9	131.6	3.7*
Microsites*Treatment	3	397.5	11.3*
Error	273	35.3	
Total	383		

Note: ns denotes not significant at 0.05 probability level; *significant at 0.05 probability level

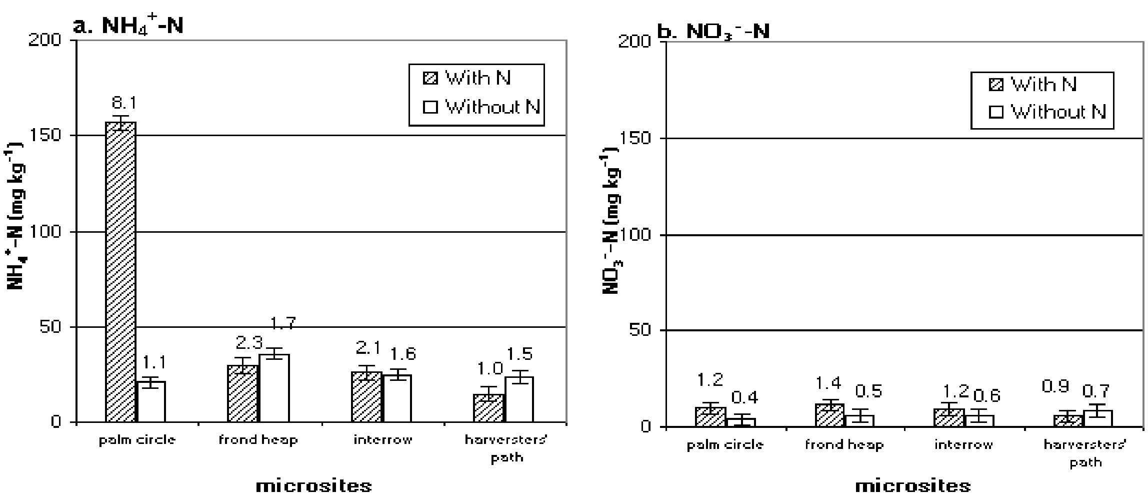

Fig. 2: Soil NH_4^+-N and NO_3^--N concentrations of in palm circle, frond heap, interrow, and harvesting path of an oil palm plantation

The harvesters' path in both treatments had the lowest NH_4^+-N contents indicating its relatively poor N fertility status. This might be due to its poor soil structure, high bulk density, relatively free of vegetation and high traffic particularly during the harvesting and maintenance operations[8]. Therefore, it might be advisable to reduce the area of harvesters' path to its minimum. Soil NO_3^--N contents although generally higher in the N treated plots were generally low (<12 mg kg^{-1}) in both treatments Fig. 2. This was probably due to the low rate of nitrification particularly at low soil pH[22,23], rapid root uptake of inorganic N and the leaching of NO_3^--N beyond the sampling depth of 30 cm. Further work is required to ascertain the downward movements of both NH_4^+-N and NO_3^-N to the lower depths and outside the rooting zone.

The CVs for soil NH_4^+-N were generally high ranging from 32% in area without N to more than 57% in area with N application (Table 2). The higher soil N variabilities in the frond heap and interrow areas of N treated oil palms might be due to their variable, lusher ground vegetation and probably greater differences in palm N status; both will affect the N nutrient cycling and soil N status. There was also a general trend showing lower variability in NH_4^+-N contents in the palm circles of both treatments. The CVs for NO_3^--N contents were very high and exceeded 65%. Again, they were higher in N treated plots for all the microsites. The reason for this is still uncertain but probably related to the nitrification process which should be more stable in plots without N application due to their low and relatively uniform NH_4^+-N contents (Table 2).

Semivariance Analysis: The component of variance calculated from the repeated measures analysis of variance (ANOVA) does not distinguish between the spatial and random variation nor the variance structure. However, this can be overcome with a plot of semivariogram, which illustrates the relationship between the sample variance and the sample distance, and distinguishes between the random and spatial variance components[24]. Thus, semivariance analysis was conducted to examine the structure of variation of soil NH_4^+-N in the oil palm plantation.

Anisotropic examination of the semivariograms showed that the spatial variability of soil NH_4^+-N was not influenced by the directions of the sampling points and therefore, isotropic model was fitted to the experimental semivariogram. A double spherical model was observed in the area with N application Fig. 3a and b. The variance generally increased with the lag distance reaching a plateau at about 35 m before

Table 2: Mean and coefficient of variation (CV) of soil inorganic-N in each microsite

		NH_4^+-N		NO_3^-N	
	Site	Mean (mg kg^{-1})	CV (%)	Mean (mg kg^{-1})	CV (%)
With N	PC	156.7	36.0	9.9	80.8
	FH	29.5	53.2	11.3	85.8
	I	25.8	57.4	9.3	88.2
	HP	14.7	46.3	5.4	96.3
Without N	PC	21.0	36.7	4.0	73.0
	FH	35.7	32.2	5.8	65.5
	I	24.8	45.2	5.8	72.4
	HP	23.6	44.1	8.4	76.2

Note: PC, FH, I and HP denote palm circle, frond heap, interrow, and harversters' path, respectively

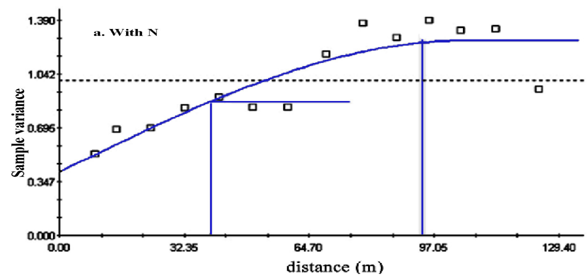

Fig. 3a: Spatial structure of soil NH_4^+-N with fertilization application of an oil palm plantation

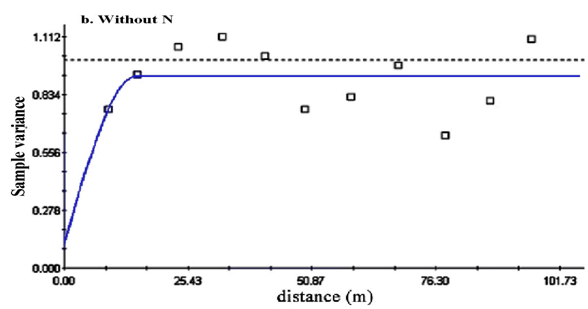

Fig. 3b: Spatial structure of soil NH_4^+-N without fertilization application of oil palm plantation

increasing again to another plateau at a distance of about 97 m. The first plateau could be related to sampling plot size of 12 (3×4) oil palms where 35 m was about 4-palm distance. The distance between the two peaks was 62 m which corresponded well to the distance between the centroids of two sampling plots. The presence of the two spherical models also suggested that the variation within the plots was relatively smaller compared with the variation between the plots. The results further indicated that the spatial structure of the semivariogram could be influenced by the sampling pattern and experimental plot size[25].

Another semivariogram was constructed using data collected from the palm circles only, where fertilizer was applied, to further examine the spatial structure of variance caused by the long-term N applications. Apart from the short range variation at distance <33 m, the semivariograms for both treatments Fig. 4a and b were similar to those obtained with data from all microsites Fig. 3a and b. This suggests that the spatial structure of NH_4^+-N in the trial site was probably also enhanced by the continuous applications of N fertilizer in the palm circle. The maximum spatial variance was reached at 90 m in area with N application and 10 m in the area without N fertilizer. This suggests that the applications of N fertilizer induced higher spatial variation or soil N heterogeneity by accentuating the NH_4^+-N content around the palm circle. This result agreed with the work of Bouma and Finke[26] but contradicted those of PanGonzalez *et al.*[27] who showed that fertilization and cultivation tend to promote soil homogeneity. The variance in the area without N showed that the soil NH_4^+-N contents were generally randomly distributed or have short spatial range of about one palm distance (Fig. 4b).

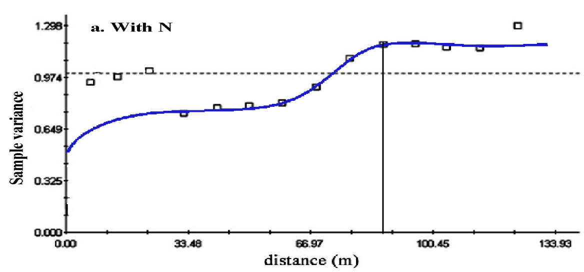

Fig. 4a: Spatial structure of soil NH_4^+-N in fertilized palm circles only of oil palm plantation

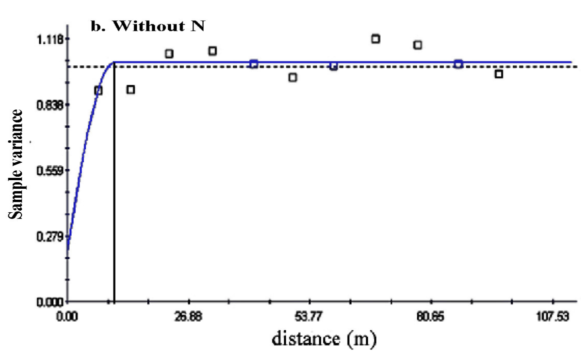

Fig. 4b: Spatial structure of soil NH_4^+-N in fertilized palm circles only of oil palm plantation

Another important feature which was observed from the semivariogram of area with N applications was the high variance at distance less than 30 m. This short range variance could be attributed to intra-correlation between the microsites as reported by Goh *et al.*[8] Journel and Huijertberg[18] described this phenomenon as the presence of local or 'quasi-stationarity' variance at short distances of separation between the microsites. Therefore, for mature oil palms where the roots and canopies are fully developed, fertilizer should be broadcast in the interrows and frond heaps to reduce the variation.

Spatial Soil NH_4^+-N Map in Oil Palm Agroecosystem: The soil NH_4^+-N content in each microsites was point kriged by using the spherical model of the semivariogram. This was the best model based on Akaike Information Criterion. The long-term applications of N fertilizer resulted in patches of high soil NH_4^+-N content in the 0-15 cm as shown in Fig. 5. The hot spots of NH_4^+-N corresponded to the exact locations of individual oil palms where N fertilizer was applied, except for the lower soil NH_4^+-N in some of the palm circles in plot B13 at the northern part of the field and plot B8 at the western portion of the field. The lower NH_4^+-N contents in parts of the latter plots required further work to ascertain it.

The appearance of the hot spots of NH_4^+-N in the area with N implied that lateral movement of NH_4^+-N to other microsites was minimal. Thus, poaching of NH_4^+-N by neighbouring oil palms might not be substantial since the amount of feeder roots decreased significantly after 2 m from the palm bases[28]. Therefore, trenching is perhaps unnecessary in fertilizer response trial of oil palm if sufficient guard rows or border palms are provided.

Without N fertilizer input, there was a gradual change in soil NH_4^+-N moving from lower contents in the northeastern stretch to the higher levels in the southern portion of the field (Fig. 5). The depletion of soil N was accompanied by a decline in ffb yield in the control plots without N. However, the kriged soil maps showed that the depletion of NH_4^+-N was non-uniform despite 9 years of N withdrawal and the oil palms had probably settled into a steady-state condition.

Effects of Long Term N Manuring on Soil Chemical Properties in the Palm Circles: The relationship between soil NH_4^+-N and NO_3^--N in the top 0-15 cm and its lower depth was investigated by correlation analysis. No significant differences were obtained for both NH_4^+-N and NO_3^--N in the areas with and without N application between the 2 depths (Table 3). This

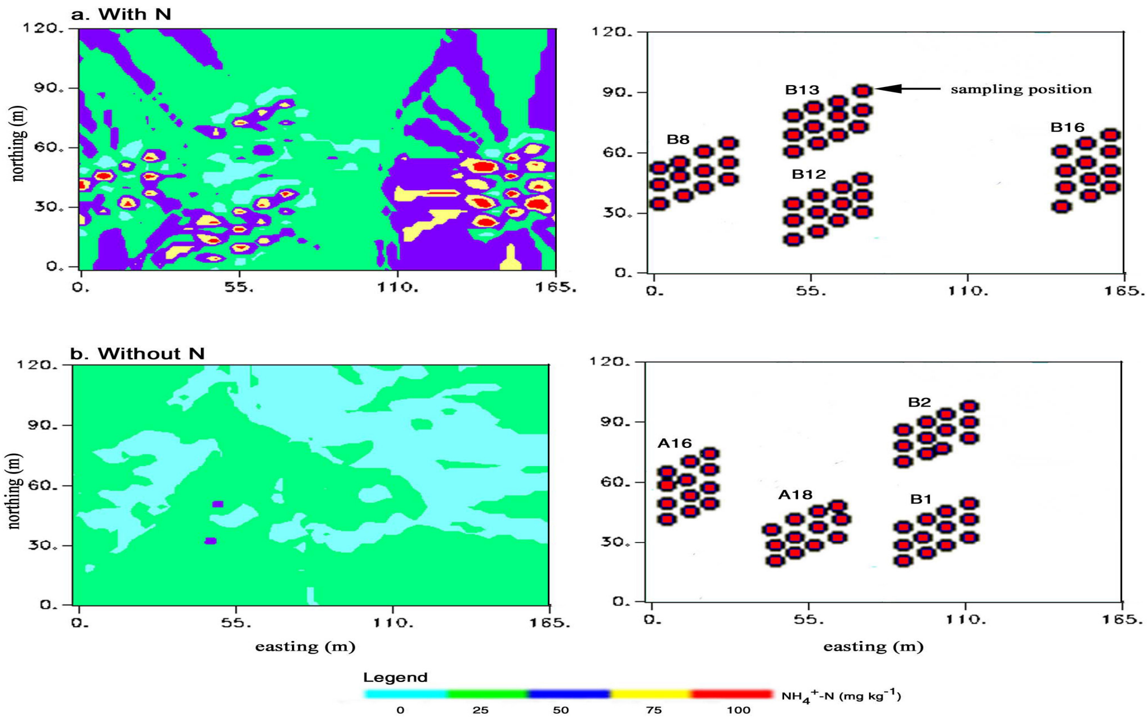

Fig. 5: Spatial Soil NH_4^+-N Map in Oil Palm Agroecosystem

Table 3: Correlation coefficient (r) values of selected soil chemical properties between 0-15 cm depth (D1) and 15-30 cm depth (D2) in the palm circle, n = 12

	NH_4^+-N (D1)	NH_4^+-N x (D1)	NO_3^--N (D1)	NO_3^--N (D2)	K (D1)	K (D2)
a. With N						
NH_4^+-N (D1)	1.00	0.40^{ns}	0.63^{*}	-0.25^{ns}	0.05^{ns}	0.07^{ns}
NH_4^+-N (D2)		1.00	0.21^{ns}	0.22^{ns}	0.38^{ns}	0.74^{*}
NO_3^--N (D1)			1.00	-0.13^{ns}	0.29^{ns}	0.08^{ns}
NO_3^--N (D2)				1.00	0.43^{ns}	0.42^{ns}
K (D1)					1.00	0.64^{*}
K (D2)						1.00
b. Without N						
NH_4^+-N (D1)	1.00	-0.02^{ns}	-0.02^{ns}	-0.06^{ns}	0.22^{ns}	0.31^{ns}
NH_4^+-N (D2)		1.00	-0.07^{ns}	0.44^{ns}	-0.54^{ns}	-0.44^{ns}
NO_3^--N (D1)			1.00	-0.20^{ns}	-0.10^{ns}	-0.04^{ns}
NO_3^--N (D2)				1.00	0.21^{ns}	0.31^{ns}
K (D1)					1.00	0.93^{*}
K (D2)						1.00

Note: ns denotes not significant at 0.05 probability level; *significant at 0.05 probability level.

Table 4: Comparison of selected soil chemical properties in the 0-15 cm depth (D1) and 15-30 cm (D2) of the palm circle averaged over both K treatments

		pH	N (%)	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})
With N	D1	3.67±0.07^{+}	0.17±0.01	155.1±20.2	9.7±2.2
	D2	3.65±0.04	0.10±0.01	86.3±17.3	3.2±1.5
Without N	D1	4.17±0.08	0.15±0.01	22.9±3.5	4.1±0.9
	D2	4.23±0.07	0.09±0.01	10.3±2.1	nd

Note: $^{+}$ mean±SE; nd: not detected

suggests that the vertical movement of both NH_4^+-N and NO_3^--N could not fully explain their respective contents at the lower depth. Thus, uptake of soil inorganic N by the oil palms might be a major process affecting the variability of soil N between the two soil depths.

The continuous applications of N fertilizer in the palm circle significantly depressed soil pH to 3.67 in the topsoil and 3.65 in the subsoil (Table 4). This is consistent with the results of other studies[7,8]. The low soil pH can be ascribed to the proton release from nitrification of NH_4^+-N to NO_3^--N (29, 30, 31,) within the palm circle. Therefore, it might be better to broadcast the N fertilizer in the interrows to avoid soil acidification, which could cause soil degradation and be detrimental to the oil palms.

The application of ammonium fertilizer in plots with K application caused a sharp decline in exchangeable K from 1.47 cmol (+) kg^{-1} to 0.78 cmol (+) kg^{-1} (Fig. 6). This might be attributed to the high NH_4^+-N content which will displace the K^+ ion from the soil complex to the soil solution resulting in higher leaching of K to the lower depth, particularly in the 1:1 clay type soil in the experimental site (32). This contention is also supported by a significant negative correlation between K and NH_4^+-N at the lower depth. The nitrification of NH_4^+-N to NO_3^--N and the presence of Cl^- from the ammonium chloride fertilizer used in the experiment will act as carriers for the K and therefore, further promote the downward movement of K.

CONCLUSIONS

The spatial variation of soil NH_4^+-N was influenced by the previous planting practices, sampling design, and experimental plot size. Application of N fertilizer in the palm circles induced higher spatial variability within the palm bases of the oil palms in the experimental site. It also resulted in localized spots of high NH_4^+-N content in the plantation. This seems to cause the downward movement of NH_4^+-N and exchangeable K to the lower depth of 15-30 cm and reduce soil pH to below 3.7. Thus, it is probably beneficial to broadcast the N fertilizer widely in the interrows and frond heaps to reduce the above detrimental effects. The lateral movement of NH_4^+-N from the area of N application (palm circle) to the other neighbouring microsites appeared to be minimal.

REFERENCES

1. Chapas, L.C. 1961. Plot size and reduction of variability in oil palm experiment. Emp. Journal. Experimental Agriculture, 29: 212-224. Thomas Telford Publishing, London, pp: 12 - 28.
2. Goh, K.H. and A. Alwi, 1988. Uniformity trials with oil palms in Malaysia. In: Oil Palm/Palm Oil Conf.: Progress and Prospects (Eds.) Halim, A.H. P.S. Chew, B.J. Wood and E. Puspharajah. Palm Oil Research Institute of Malaysia and International Society of Planters, Kuala Lumpur pp: 667-684.
3. Soh, A.C., C.H., Lee, Y.Y. Yong, C.W. Chin, Y.P Tan, N. Rajanaidu and P.K. Phuah, 1989. The Precision of Oil Palm Breeding Experiments in Malaysia. In: Applications of Statistics to Perennial Tree Crops (Eds.) Soh, A.C., N. Rajanaidu and M.H.B. Nasir. Palm Oil Research Institute of Malaysia, Kuala Lumpur, pp: 41-50.
4. Ng, S.K. and K. Ratnasingam, 1970. Soil heterogeneity and field sampling for chemical analysis of Malaysian soils. In: First ASEAN Soils Conference. Bangkok, Thailand, pp: 40..
5. Law, W.M. and M.M. Tan, 1977. Chemical properties of some Peninsular Malaysian soil series. In: Proceedings of Chemistry and Fertility of Tropical Soils. Malaysian Society of Soil Society, Kuala Lumpur pp: 180-191.
6. Goh, K.J., K.K. Kee and P.S. Chew, 1998. Soil Fertility Status of Some Common Soils in Sabah, Malaysia. In: Proceedings of the Soil Science. Conference. of Malaysia 1993 (Eds.) Aziz, B. and A.M.S. Husni Malaysian Society of Soil Society, Kuala, Lumpur pp: 1-16.
7. Kee, K.K., K.J. Goh and P.S. Chew, 1995. Effects of NK fertiliser on soil pH and exchangeable K Status on Acid Soils in an Oil Palm Ecosystem in Malaysia. In: Plant-Soil Interactions at Low pH: Principles and Management (Eds.) Date, R.A. N.J. Grundon, G.E. Rayment and M.E. Probert Developments in Plant and Soil Science, Kluwer Academic Publications, The Netherlands pp: 809-815.
8. Goh, K.J., P.S. Chew and K.K. Kee, 1996. Spatial Soil Fertility in Mature Oil Palm Agroecosystem and its Implications on Fertiliser Management. In: Proc. of the Soil Sc. Conf. of Malaysia 1995 (Eds.) Aminuddin, B.H., A.B. Ismail, A.R. Ahmad and M.Z. Ghazali Malaysian Society of Soil Science, Kuala Lumpur pp: 80-90.
9. Goh, K.J., Tee, B.H., A.R. Anuar and C.Y. Woo, 2000. Spatial yield variation of oil palm in a fertiliser response trial in Malaysia. Proceedings. of the Soil Science Conference of Malaysia 2000. Malaysian Society of Soil Science, Kuala Lumpur.
10. McBratney, A.B. and J.A. Taylor, 2000. PV or not PV? Proceedings. of the 5th International Symposium on Cool Climate Viticulture and Oenology- a Workshop on Precision Management. Melbourne, Australia pp: 10.
11. Keeney, D.R. and D.W. Nelson, 1982. Nitrogen-Inorganic Forms. In: Methods of Soil ed. (Eds.) Page, A.L., R.H. Miller and D.R. Keeney. Analysis Part 2. 2nd Agron. Monograph 9. ASA, CSSA, SSSA, Madison, Winsconsin pp: 643-698.
12. Knudsen, D., G.A. Peterson and P.F. Pratt, 1982. Lithium, sodium, and potassium. In: Methods of Soil Analysis (Eds.) Page, A.L., R.H., Miller and D.R. Keeney Part 2.2ndp. Agron. Monograph 9. ASA, CSSA, SSSA, Madison, Winsconsin pp: 225-246.

13. Bremner, J.M. and C.S Mulvaney, 1982. Nitrogen-total. In: Methods of Soil Analysis. (Eds.) Page, A.L., R.H. Miller and D.R. Keeney. Part 2.2nd Agron. Monograph 9. ASA, CSSA, SSSA, Madison, Winsconsin pp: 595-624.
14. Little, R.C., 1989. Statistical analysis of experiment with repeated measurements. Hort. Science. 24: 37-40.
15. Sokal, R.R. and F.J. Rohlf., 1995. Biometry: The principles and practices in biological research. 3rd ed. Freeman, W.H., New York. pp: 859.
16. Crowder, M.J. and D.J. Hand, 1990. Analysis of repeated measures. Chapman and Hall, London. pp: 257.
17. SAS Inst. 1989. SAS/STAT guide for personal computers. Version 6, 4th ed. SAS Inst. Inc. Cary, NC. pp: 846.
18. Journel, A.G. and N.J. Huijbergts, 1978. Mining geostatistics. Academic Press. New York, 600 pp.
19. Burgess, T.M. and R. Webster, 1980. Optimal interpolation and isarithmic mapping of soil properties. I. The semi-variogram and punctual kriging. Journal of Soil Science, 31: 315-331.
20. Webster, R. and A.B. McBratney, 1989. On the akaike information criterion for choosing models for variograms of soil properties. Journal of Soil Science, 40: 493-496.
21. Kee, K.K., K.J. Goh and P.S. Chew, 2000. Water cycling and balance in mature oil palm agroecosystem in Malaysia. In: International Planters Conference on Plantation Tree Crops in the New Millennium: The Way Ahead (Eds.) Puspharajah, E. International Society of Planters, Kuala Lumpur pp: 251-275.
22. Strong, D.T., P.W.G. Sale and K.R. Helyar, 1997. Initial soil pH affects the pH at which nitrification cease to due to self-induced acidification of microbial microsites. Australian Journal of Soil Research 35(3): 565-570.
23. Paavolainen, L., M. Fox and A. Smolander, 2000. Nitrification and denitrification in forest soil subjected to sprinkling infiltration. Soil Biology and Biochemistry, 32(5): 669-678.
24. McBratney, A.B., B.M. Whelan, J.A. Taylor and M.J. Pringle, 2000. A management opportunity index for precision agriculture. In: Proceedings of the 5th International Conference on Precision Agriculture and other Resource Management (Eds.) Robert, P.C., R.H. Rust and W.E. Larson. In Press. South, Bloomington, Minnesota.
25. McBratney, A.B. and M.J. Pringle, 1997. Spatial variability in soil- implications for precision agriculture. In: Precision Agriculture'97: Spatial Variability in Soil and Crop (Eds.) Stafford, J.V. BIOS Scientific Publishers, United Kingdom 1: 3-31.
26. Bouma, J. and P.A. Finke, 1993. Origin and nature of soil resource variability. In: Soil Specific Crop Management. (Eds.) Robert, P.C., R.H. Rust and W.E. Larson. ASA, CSSA, SSSA, Madison, Winsconsin pp: 3-14.
27. PanGonzalez, A., S.R. Vieira and C.M.T. Taboada, 2000. The effect of cultivation on the spatial variability of selected properties of an umbric horizon. Geoderma, 97 (3-4): 273-292.
28. Schroth, G., M.R.L., Rodrigues, S.A.D. Angelo, 2000. Spatial patterns of nitrogen mineralization, fertilizer distribution and roots explain nitrate leaching from mature Amazonian oil palm plantation. Soil Use and Management 16: 222-229.
29. Goh, K.J. (Unpublished) Applied Agricultural Research Sdn. Bhd., Locked Bag 212, Sg. Buloh Post Office, 47000 Sg. Buloh, Selangor, Malaysia.
30. Thomas, G.W. and W.L. Hargrove, 1984. The chemistry of soil acidity. In: Soil Acidity and Liming. 2nd (Eds.) Adams, F. ASA, CSSA, SSSA, Madison, Winsconsin pp: 3-56.
31. Berg, N.A., 1986. Effects of 20 years of low N rate pasture fertilisation on soil acidity. Journal of Range Management, 39: 122-124.
32. Schwab, A.P., C.E. Owensby, S. Kulyingyong, 1990. Changes of soil chemical properties due to 40 years of fertilization. Soil Science, 149: 37-43.
33. Juang, T.C., H.J., Chen and K.L. Houng, 1993. The effect of the specific adsorption of anions on ammonium fixation. Journal of Agriculture and Forestry, 42(2): 19-30.