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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation

Soil Characteristics and Nutrients Dynamics of An Oil Palm Plantation in Central Pahang, Malaysia

(マレーシア国パハン州のアブラヤシ農園における土壌特性と養分動態）

学位論文要約：
Dissertation Summary

Oil palm is one of the most planted oil crop in Malaysia and Indonesia and the industry has experienced rapid expansion in total planted area in the recent years. It is estimated that additional area of 38 million hectares for oil palm cultivation is required by the time in 2050 to support global vegetable oil demand. In spite of the prosperous development of oil palm, the cultivation has been deemed controversial, in particular, for causing deforestation. In addition, problems such as lost of biodiversity, green house gas emission, pollution treat from oil palm mill waste (palm oil mill effluents) and dispute over cultivation on customary land and territories of the indigenous people were also reported. In view of this, environmentalist and conservationists suggested that existing crop land for oil palm cultivation should be used more sustainably and without causing degradation effect to the environment.

In an oil palm plantation, the cultivation is heavily dependent on the use of fertilizer because of intrinsically poor nutrient status of ultisols and oxisols where most of oil palm plantations are located. For mineral soils, the macro nutrient inputs that are applied include Nitrogen (N), Phosphorus (P) and Potassium (K) in the forms of sulfate of ammonia, phosphate rocks and Muriate of Potash, respectively. For micro nutrients, the input applied is Boron (B) in the form of sodium borate. The fertilizers are generally applied around palm trunks with a diameter of one to two meters where weeds are clear-slashed (called as weeded

circle). For N and K fertilizers, these elements are also placed, at a lesser extent, at the inter row of palms with organic matter placement for fields with 6 years of planting age and above.

On the other hand, organic residue from the field operation is placed within the field for mulching purpose as well as to recycle plant nutrients back to the soils. In the oil palm field, fronds which are pruned off upon harvesting fruit bunches are heaped up in-between palm trees as mulching material during cultivation (called as frond heap). The frond heap represents about 20% of the area in the field and the decomposition of fronds takes about 12-18 months. It was estimated that approximately 10 t ha^{-1} yr^{-1} dry matter of fronds are cut in mature oil palm plantations. Meanwhile, other organic residue includes empty fruit bunches which are produced during the oil mill process are occasionally applied to weeded circles as mulching material, this technique has been examined since 2000s and is still uncommon.

So, there are two important pathways to supply nutrient to soils through usual management practices; one is external input by chemical fertilizer application, while the other is the internal recycling pathway of organic matter and its nutrient through plant residue application to soils. A usual oil palm field is composed mainly of micro sites which are differently managed; 1) weeded circle, 2) frond heap and, in addition, 3) harvest path, which is the operation path for workers to harvest and transport fruit bunches without any application of fertilizer and organic residues.

At present, soil properties have been extensively reported under oil palm plantation by the side of palm oil producers such as local research institutions and oil palm companies. Many of the studies have used a field which is located on a relatively flat land and well-managed as the study site and have been concerned with changes in soil properties at the area applied with fertilizer or organic matter, aiming at evaluating their efficiency as well as improving yield. Information is still lacking on the spatial differentiation of soil nutrient status within one field on undulating topography under actual plantation operation. In addition, less study focus has been given to the soil information in oil palm plantation in terms of its management effects on the environment; because of the long economic lifespan of oil palm, the soil nutrient dynamics is expected to be different over time taking into consideration the continuous field management at the specific micro sites. The understanding of the effect of continuous application of fertilizer (such as P) at the weeded circle and organic matter placement at the frond heap to the soils during the whole economic lifespan of oil palm cultivation is crucial to know the fate of soil nutrients which can be used to contribute to better environment conservation as well as better field management design. This is particularly important as the current oil palm plantation will be most likely to be replanted with the same crop for an unknown number of times in the future.

Therefore, for the development of a eco-friendly and sustainable oil palm management system, 3 studies were set up; 1) to characterize the soil profile and investigate the spatial heterogeneity of nutrients exist in the oil palm field as well as the effect of slope on cultivation, 2) to evaluate the soil organic matter status among the micro sites and its accumulation effect in the oil palm field, and 3) to assess the distribution of soil phosphorus of oil palm field as influenced by fertilizer and frond heaping practices. In this study, I selected the Jengka Triangle area in central Pahang, Peninsular Malaysia, which is now the biggest commercial oil palm cultivation area in the peninsular.

Study 1) An oil palm field with an average 8° slope was selected. Fundamental information was established that related to soil properties at the weeded circle, frond heap and harvest as well as slope topograpy. Overall, the soils can be described be as clayey kaolinitic, highly weathered, acidic, low in cations while the soil hardness increased with depth. The soil was classified as Typic Hapludox belonging to the Oxisols according to the USDA classification system. Observation of the soil profile showed that soil moisture permeability was relatively good and most oil palm root concentrated between 10 cm to 60 cm from the soil surface. Soil properties were significantly or tended to be different at the depth of 0-5 cm and 5-10 cm in terms of micro sites (Figure 1); pH level, total carbon (T-C), total nitrogen (T-N) and exchangeable calcium (Ca) contents were higher at the frond heap. On the other hand, higher amounts of available phosphorus were accumulated in the weeded circle due to fertilizer application. Meanwhile, between different slope positions, non-distinct soil particles movement was observed and no evidence of soil erosion was found.

Study 2) Soil samples were collected from three oil palm commercial fields located closely with different planting age; five years (OP 5), ten years (OP 10) and 18 years (OP18). Results showed that the total carbon (T-C) and total nitrogen (T-N) were high at the weeded circle and frond heap compared to those at the harvest path in all the fields (Figure 2). This was attributable to the decomposition of placed fronds and decomposition of root biomass at the frond heap and the weeded circle, respectively. In terms of different planting age, the T-C and T-N content at the weeded circle tended to be the highest in OP 18, suggesting accumulation of soil organic matter at the weeded circle over time. For minerals N, the application of ammonium fertilizer resulted in higher ratio of NH_4^+ at the weeded circle and frond heap than the harvest path. Meanwhile, the level of soil microbial biomass C was the highest at the weeded circle. Comparison between different planting fields showed that the level soil microbial biomass C increased with time for all the micro sites.

Study 3) The soil sampling design was same with those in study 2; three oil palm fields with different planting ages were selected. From the results, the distribution of soil P varied widely with different management practices; the levels of total P and Bray II P, inorganic $NaHCO_3$ P and NaOH P, and HCl P at 0-3 cm were higher at the weeded circle than those at the frond heap and harvest path due to continuous P fertilization through which a significant portion of the applied phosphate rocks remained undissolved and was gradually accumulated in soils (Table 1 and Table 2); such P accumulation tended to be more obvious in OP 18. Meanwhile, the levels of organic P fractions at the frond heap were similar to those at the harvest path and lower than those at the weeded circle. The levels of P at 30-40 cm were not virtually different among the micro sites.

Based on these findings, alternative field management program should be tested and developed; 1) for soil fertility diagnosis in an oil palm field, soils samples should be taken from the frond heap, weeded circle and harvest path to understand the nutrient variation existed in field in order to have better judgement in nutrient management. 2) In order to improve the efficiency of the fertilizer, the fertilizer should be mixed with the soils of the frond heap and weeded circle for better oil palm root uptake. 3) For P fertilizer, application should be more concentrated at an early stage after transplanting to promote the saturation of Fe and Al oxides with P so that subsequently-added P would be more plant available; and at the later stages the fertilizer rate can be reduced. 4) During planting stage, young palm trees can be transplanted to the previous weeded circle in order to utilize the rich soil nutrients. 5) For oil palm planting at gentle slope, the design of vehicle road and placement of frond heap should be taken into consideration to reduce the surface runoff of soils nutrients.

These proposed strategies should be tested in the actual fields and compared with the current practices. For future studies, the amount of nutrients (macro and micro) that are contributed from the frond heaping practices should be further evaluated. In addition, plant nutrients from fronds and root biomass that can be incorporated into the soils system should be addressed to understand in more detail the process of nutrient recycling in oil palm field. In terms of fertilizers, due to the prolonged application, trace elements in the fertilizer should be monitored; for example, the presence of heavy metal in the P fertilizer (phosphate rocks) should be assessed and its effect on the soils should be studied.

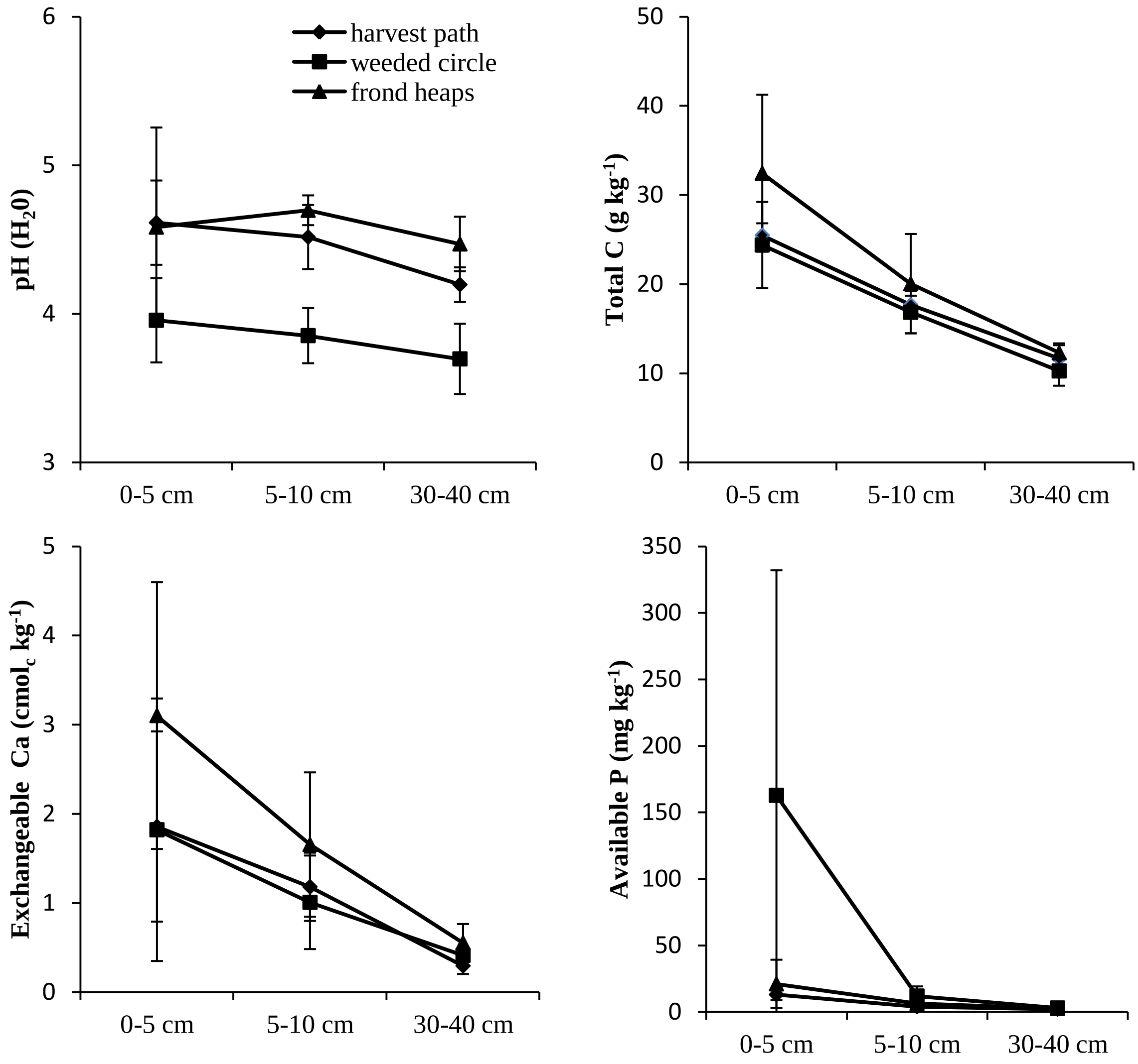

Figure 1 Selected soil properties of micro sites at different soil depths.
Data were indicated in mean with standard deviation.

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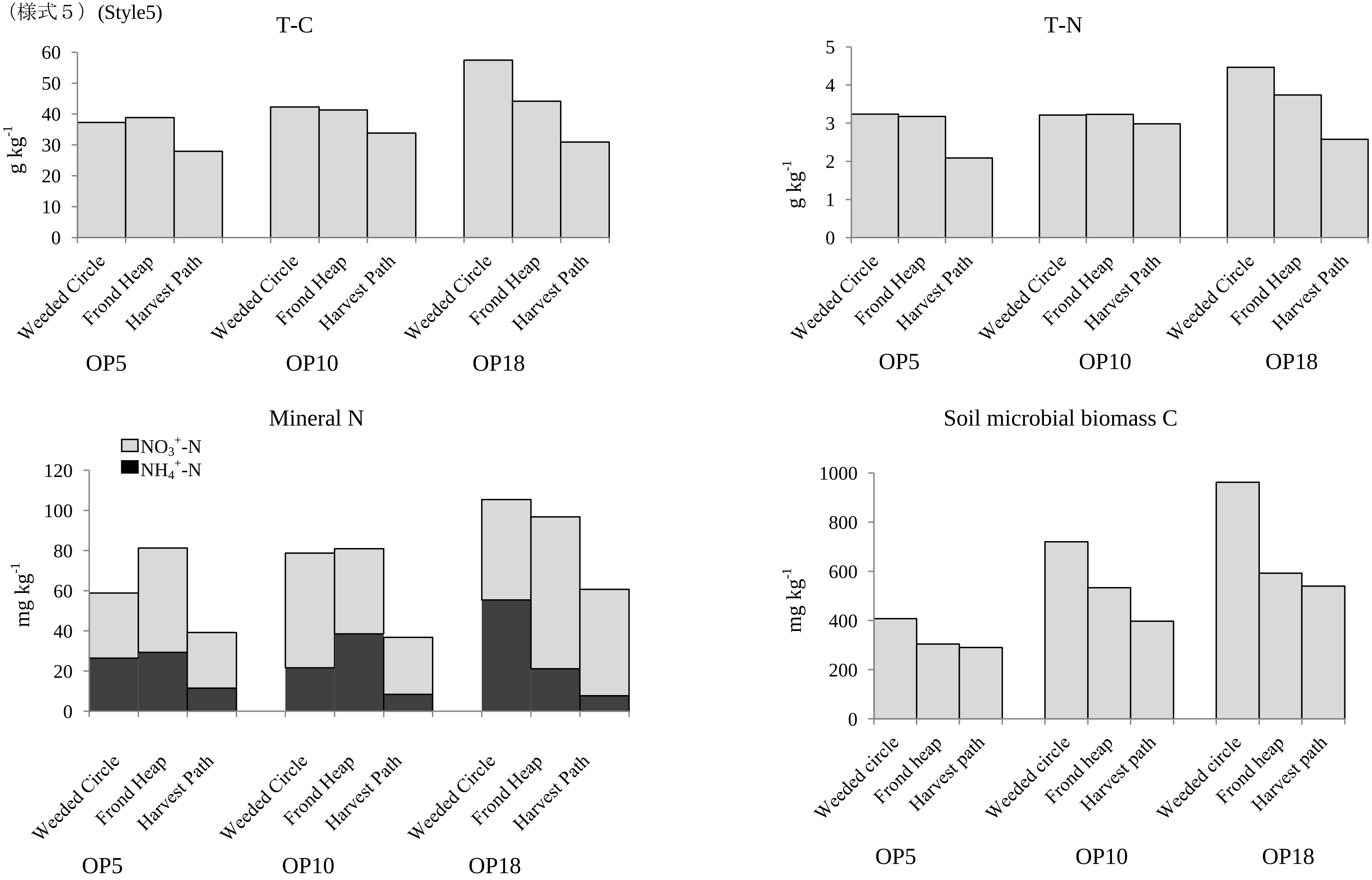

Figure 2 T-C, T-N, mineral N and soil microbial biomass C at micro sites in oil palm fields with different planting ages at 0-3 cm soils.

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Table 1 The averages of Bray II P and total P at micro sites in oil palm fields with different planting ages.

Planting age	Micro site	Bray II P mg P kg^{-1}		Total P mg P kg^{-1}	
0-3 cm					
OP5	Weeded circle	1062 ± 122	a	1894 ± 115	a
	Frond heap	352 ± 275	b	862 ± 439	b
	Harvest path	175 ± 99.6	b	625 ± 109	b
OP10	Weeded circle	2392 ± 1755	a	4476 ± 2361	b
	Frond heap	19.8 ± 3.94	b	288 ± 39.9	b
	Harvest path	26.0 ± 11.9	b	408 ± 115	b
OP18	Weeded circle	4256 ± 2613	a	8345 ± 4963	b
	Frond heap	14.0 ± 2.80	b	347 ± 100	b
	Harvest path	33.1 ± 37.5	b	277 ± 60.1	b
3-10cm					
OP5	Weeded circle	87.6 ± 34.4		404 ± 43.7	
	Frond heap	427 ± 540		737 ± 590	
	Harvest path	271 ± 215		614 ± 281	
OP10	Weeded circle	286 ± 298		933 ± 715	
	Frond heap	12.5 ± 2.23		236 ± 45.1	
	Harvest path	12.0 ± 3.62		215 ± 83.3	
OP18	Weeded circle	1450 ± 1539		2008 ± 1666	
	Frond heap	10.8 ± 1.45		212 ± 82.6	
	Harvest path	5.75 ± 1.28		93.9 ± 21.6	

Values followed by a different letter (a, b) in a column indicate that means are significantly different between different micro sites within each site while values without letter indicate that means are not significantly different ($P<0.05$). Data are mean ± standard deviation.

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Table 2 The averages of different P fractions at micro sites in oil palm fields with different planting ages.

Planting age	Micro site	$NaHCO_3$ P_i		$NaHCO_3$ P_o		NaOH P_i		NaOH P_o		HCl P		Residual P	
		mg P kg^{-1}		mg P kg^{-1}		mg P kg^{-1}		mg P kg^{-1}		mg P kg^{-1}		mg P kg^{-1}	
0-3cm (n=5)													
OP5	Weeded circle	324 ± 105	a	51.5 ± 28.8	a	770 ± 110	a	255 ± 214		226 ± 157		288 ± 278	a
	Frond heap	45.3 ± 30.8	b	22.1 ± 10.9	b	291 ± 134	b	141 ± 26.1		155 ± 228		224 ± 210	b
	Harvest path	33.9 ± 15.1	b	17.1 ± 7.01	b	330 ± 105	b	147 ± 27.8		32.2 ± 20.6		65.1 ± 51.9	b
OP10	Weeded circle	421 ± 178	a	80.6 ± 92.5		1256 ± 364	a	459 ± 210	a	1390 ± 1576	a	869 ± 372	a
	Frond heap	10.8 ± 2.08	b	14.9 ± 2.65		130 ± 22.3	b	117 ± 44.6	b	1.70 ± 0.54	b	33.4 ± 27.4	b
	Harvest path	10.5 ± 2.16	b	14.9 ± 3.73		215 ± 92.4	b	151 ± 16.7	b	2.17 ± 1.81	b	19.1 ± 19.0	b
OP18	Weeded circle	273 ± 132	a	38.3 ± 30.4		1110 ± 77.2	a	563 ± 73.5	a	4806 ± 4173	a	1554 ± 822	a
	Frond heap	10.3 ± 2.18	b	13.8 ± 2.95		110 ± 32.8	b	147 ± 69.6	b	5.02 ± 2.24	b	65.8 ± 37.8	b
	Harvest path	9.13 ± 3.90	b	10.2 ± 2.22		138 ± 55.1	b	77.7 ± 47.1	b	4.74 ± 3.59	b	48.1 ± 37.0	b
3-10cm (n=3)													
OP5	Weeded circle	28.6 ± 5.57		10.3 ± 0.86		244 ± 58.4		106 ± 74.0		4.70 ± 1.37		17.1 ± 11.4	
	Frond heap	30.9 ± 13.6		12.5 ± 1.00		272 ± 115		146 ± 38.5		212 ± 349		90.7 ± 124	
	Harvest path	35.2 ± 11.2		16.4 ± 10.4		330 ± 5.11		134 ± 69.3		74.0 ± 93.7		57.6 ± 61.8	
OP10	Weeded circle	112 ± 73.5		9.14 ± 3.13		568 ± 339		163 ± 56.5		17.2 ± 22.9		123 ± 175	
	Frond heap	8.19 ± 1.33		13.4 ± 3.03		98.0 ± 25.0		103 ± 49.6		1.05 ± 0.07		19.0 ± 25.6	
	Harvest path	6.94 ± 0.93		9.79 ± 4.49		133 ± 106		53.8 ± 27.2		1.20 ± 0.41		27.2 ± 22.7	
OP18	Weeded circle	162 ± 164		6.63 ± 4.55		691 ± 349	a	211 ± 300		711 ± 874		227 ± 134	
	Frond heap	7.62 ± 2.36		11.6 ± 2.52		87.9 ± 31.6	b	43.4 ± 13.8		3.49 ± 2.12		58.6 ± 33.3	
	Harvest path	3.82 ± 1.07		4.33 ± 0.19		37.8 ± 27.1	b	44.3 ± 35.9		1.81 ± 0.92		17.6 ± 14.6	

Values followed by a different letter (a, b) in a column indicate that means are significantly different between different micro sites within each site while values without letter indicate that means are not significantly different ($P<0.05$). Data are mean ± standard deviation.