Chapter 14
Soil Environment in Sago Palm Forest

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Abstract Soils (acid sulfate soils, peat soils, gley soils, and others) distributed under sago forest and their productivity of sago palm are described in this chapter. Sago palm in tropical lowland areas is growing with the formation of the communities behind the mangrove forest. The main sources of water for sago palm are rivers, which are present in the eutrophic environment and more or less affected by sea tides. Sago palm equipped with the mechanism to eliminate salt effect or regulate salt uptake in several ways can grow in brackish water. Acid sulfate soils are derived from sulfate ion (SO_4^{2-}) in seawater. Sulfate ion is reduced to form sulfide compounds by sulfate-reducing bacteria in soils (potential acid sulfate soils). Sulfide compounds are oxidized to sulfate ion and hydrogen ion is produced by sulfur- and iron-oxidizing bacteria in soils (actual acid sulfate soils). The sago starch yield is observed to be extremely high near the coast and lower in the inland places (soil pH 3.3–3.8). The tropical woody thick peat soils called Histosols in the tropical rainforest climate of Southeast Asian islands are formed to transport small amount of sediments by the shorter rivers compared to large rivers of continents. The constituent components in water flowing into tropical peat soils ensure the normal growth of sago palm. In Sarawak no effect of nitrogen (N) application on leaf production of sago palm was found, which was explained by the findings of endophytes' activities on the nitrogen fixation. The sago palm growth in Inceptisols of the Philippines and Indonesia at the different stages was larger than those in Histosols of Malaysia from the long-term growth study.

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14.1 Natural Habitat of Sago Palm in Tropical Lowland Areas

Natural lowland forest in tropical areas consists of mangrove, tropical lowland, and tropical peatland forests, in that order moving inland from the sea (Okazaki et al. 2008) (Fig. 14.1). Although distributed in both tropical and subtropical lowland areas affected by seawater, the dominant distribution of mangrove forest is present in tropical brackish water areas. Brackish water is defined as a mixture of sea- and freshwater with a salt concentration of 0.2–30 parts per thousand (‰), equivalent to 1/100–1 of the salt concentration of seawater, because seawater generally contains 33–34‰. Nipa and sago palm are present behind mangrove forest and form a large plant community. Both tropical lowland forest and tropical peatland forest are found in brackish water areas, each with a different freshwater source. Tropical lowland plants grow under relatively eutrophic nutrient conditions, while tropical peatland plants are under poor nutrient conditions and affected by rainfall and flowing groundwater with high reduction and oxidation (redox) potential (Table 14.1).

Sago palm (*Metroxylon sagu* Rottb.) is part of the formation of vegetation communities behind the mangrove forest (Yamada 1986) (Table 14.1). In the very poorly drained to swampy conditions of Papua New Guinea, sago palms and pandans (*Pandanus*) are found in the understory (Bleeker 1983). The main source of water for sago palm is the rivers, which are present in the eutrophic environment and more or less affected by sea tides (Tie and Lim 1977).

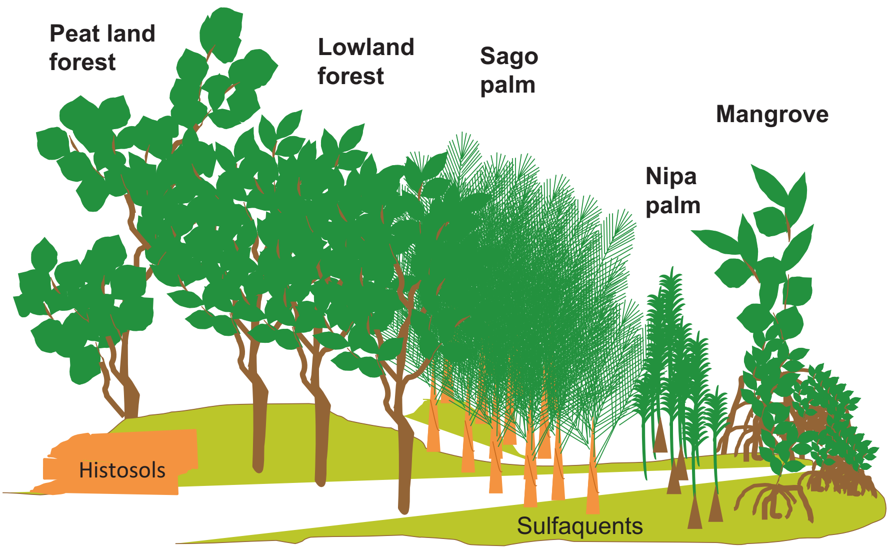

Fig. 14.1 Distribution of tropical lowland forest along the sea (Okazaki et al. 2008, partly modified)

Table 14.1 Typical tropical plant communities (Yamada 1986)

		Tropical lowland forest	
	Mangrove	Fresh water lowland forest	Brackish water lowland forest
Niche	Sea shore	Back marsh	Deeper portion of back marsh
Water	Sea to brackish water	Brackish to fresh water	Rain water
Soil	Muddy	Clayey	Peaty
Environment	Tidal area	Flooding area	Acidic stagnant/running water
Nutrient	Eutrophic	Eutrophic to Oligotrophic	Oligotrophic
Distribution	Band structure	Uncertained	Concentric circle
Species	*Rhizophora*	*Alstonia*	*Shorea albida*
	Avicennia	*Campnosperma*	*Dactylocladus*
	Bruguiera	*Palaquium*	*Gonystylus*
	Acrostichum	*Metroxylon*	*Pandanus*
	Nypa	*Oncosperma*	*Salacca*

Halophytic plants equipped with mechanisms to eliminate salt effect or regulate salt uptake in several ways can grow in brackish water. Flach et al. (1977) found that sago palm was not inhibited in a Hoagland solution of about 6–7 millisiemens (mS) per cm electrical conductivity, which corresponds to 1/7–1/8 of electrical conductivity of seawater. However, the growth rate of sago palm slowed when this range of electrical conductivity was exceeded. Many terrestrial plants suffer from a salt concentration of 0.1%, and significant growth suppression is found when it exceeds 0.3% (around 60 mmol L^{-1}) (Matoh 2002). Salt stress is divided into two types: the inhibition of water absorption due to osmotic pressure generated by salt (osmotic stress) and the excess damage caused by the specific physiological effects of the salt-constituting ions (ionic stress). Generally ionic stress is regarded as the primary factor of salinity stress. As sago palm is highly tolerant of salinity stress, it is likely to be equipped with several kinds of mechanisms. By the treatment of 0–0.2% sodium chloride solution, sago palm absorbed sodium ions from the root and translocated them to the petiole and the leaflets. However, sago palm seedlings retained sodium ions in the roots and transferred them to the lower leaves gradually (Ehara et al. 2006). Yoneta et al. (2004, 2006) determined that sago palm seedlings grew best at a salt concentration of around 10 mmol L^{-1} (1/60 of sea salt concentration), while sago palm growth was inhibited in water or in a salt concentration range of 50–200 mmol L^{-1} (Fig. 14.2). Ehara et al. (2008) cultured *Metroxylon sagu* Rottb. and *M. vitiense* for 1 month hydroponically; thereafter a 2% sodium chloride solution was used for the culture for another month. Results showed that the transpiration rate of all sago palms declined with the treatments and that the potassium content in sago palm increased with increasing sodium content in the petiole. Yoneta et al. (2006) deduced that sago palm primarily maintained a high osmotic pressure

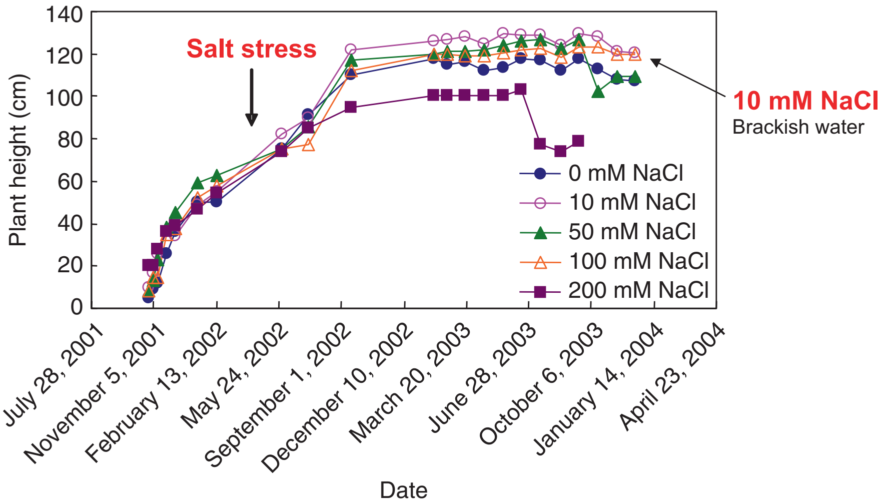

Fig. 14.2 Changes in the height of sago palms under different NaCl concentrations (Yoneta et al. 2006)

Table 14.2 Soils related to sago palm growing areas (common name, US Soil Taxonomy)

Peat soils:	Tropofibrists, Tropohemists, Troposaprists
Acid sulfate soils:	Sulfaquents, Sulfaquepts, Sulfic Tropaquents
	Sulfic Humaquents, Sulfic Haplaquepts, Sultfic Haplaquents
Gley soils:	Hydraquents, Fluvaquents, Tropofluvents
Other soil types:	Oxisols, Entisols, Inceptisols

in the cytoplasm using potassium ions as the osmotic pressure regulator (compatible solute). They concluded that small amounts of other compatible solutes such as proline and glycine betaine were produced. In addition, Ehara et al. (2003, 2006) showed that sago palm roots excluded sodium ions using the barriers to inhibit sodium ion absorption.

14.2 Soils Distributed Under Sago Palm Forest

In this chapter, soil names (common and US Soil Taxonomy names) distributed beneath sago palm forests are shown in Table 14.2.

14.3 Acid Sulfate Soils (Typic Sulfaquents, Sulfic Hydraquents, Sulfic Tropaquents, Typic Sulfihemists, etc.)

The pedogenic process of acid sulfate soils requires a source of sulfate (SO_4^{2-}: 2650 mg/L) derived from seawater and brackish water to supply organic matter as an energy source for heterotrophic bacteria (*Desulfovibrio* and *Desulfotomaculum*), resulting in the formation of S^{2-} and S^0 (Kyuma 1986). The reaction of Fe^{2+} and S^{2-} gives ferrous sulfide (FeS). Ferrous sulfide reacts S^0 to form FeS_2 (pyrite) (Figs. 14.3 and 14.4). Fe^{2+} and S^{2-} in FeS_2 are oxidized to Fe^{3+} mediated by *Thiobacillus ferrooxidans* and *Ferrobacillus ferrooxidans* and SO_4^{2-} mediated by thiobacilli groups (Fig. 14.5), respectively. Jarosite ($KFe_3(SO_4)_2(OH)_6$ and goethite (α-FeOOH) are produced which are pale yellow (2.5 Y 6/8–2.5 Y 8/8) and yellow brown (Fig. 14.6). Clayey yellow brown sediments in acid sulfate soils are called *cat clay*, which derives from the Dutch term *katteklei*.

In the 1840s, sago palm cultivated in Sarawak was grown quite successfully in some parts of the island (Borneo), and the raw sago exported in large quantities from the west coast to Singapore (Fukui 1980; cited from Low 1848). *Metroxylon sagu* is still the main food of several Papua groups in New Guinea; the inhabitants of most of the islands in the Moluccas; the southeast arm of Sulawesi; the Banggai and Sula archipelagoes east of Sulawesi; the Mentawai Islands west of Sumatra; the Melanau people in Sarawak; the east coast of Sumatra (Bengkalis); in the Riau, Karimun, and Lingga archipelagoes; and in some coastal regions in west Kalimantan (Avé 1977). The proper growing areas for sago palm are *tana nabo* (peat soils con-

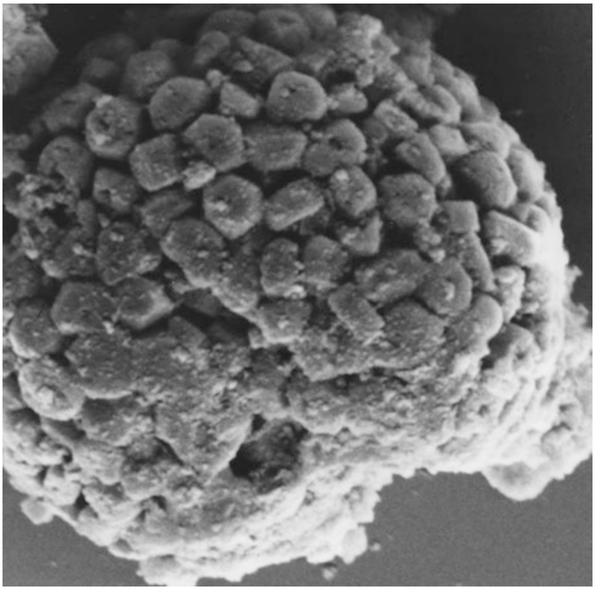

Fig. 14.3 Pyrite in acid sulfate soils

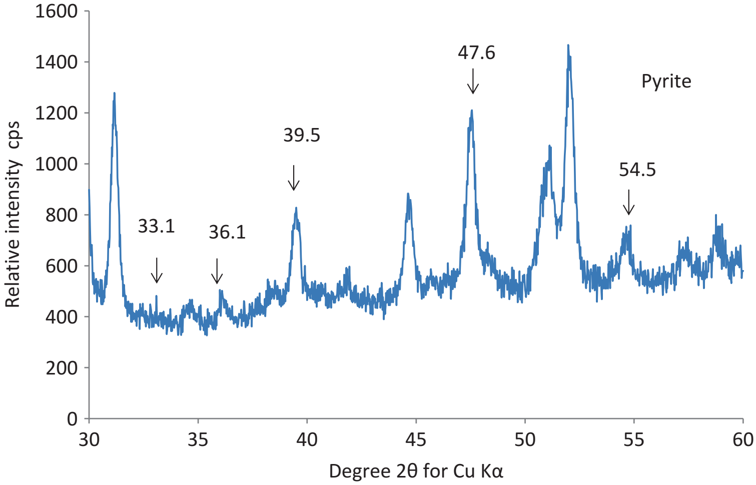

Fig. 14.4 X-ray diffraction pattern of HF-treated acid sulfate soil

Fig. 14.5 Thiobacillus in acid sulfate soils

taining alluvial sand and clay) and *tana pala* on the interfluves produced by rivers in their meandering in Sarawak (Morris 1953). The peat soils (*tana guun*) away from the river, however, give rise to fast growth of sago palm, but they are poor in sago starch content. The sago palm-growing areas, however, are often composed of alluvial soils and peat soils (Sato et al. 1979). Flach (1983) revealed that sago palm grew best in mineral soils which should be high in organic matter as opposed to peat soils and that clay soils were usually found in the natural habitat of sago palm.

The soils under sago forest in South Sulawesi, Indonesia, (Tables 14.3 and 14.4) are located in transition areas between the natural river bank and black marsh (Takaya 1983; Okazaki 1995). Soils that are already strongly acidic are called *actual acid sulfate soils* (Table 14.3), and those which become acidic after oxidation are called *potential acid sulfate soils* (Table 14.4).

Fig. 14.6 Jarosite and goethite in acid sulfate soils

Table 14.3 Soil profile in Desa Takkalala, Kabupaten Luwu, South Sulawesi, Indonesia (Takaya 1983, partly modified)

Profile A (Center of sago forest)
3–0 cm, L, litter horizon, sago and other leaves
0–82 cm, B, light gray color in matrix, coarse texture, bright brown (7.5 YR 5/6 to 5/8) to brown (7.5 YR 4/3 to 4/6) of tube type mottles with diffusing outside, 2–3 cm structure in diameter, present gley mottles, many fresh and old sago roots (5–7 mm in diameter) in the structure, yellow (fresh roots) and black (old roots) color roots surrounded by blue gray (reduced) color parts

Table 14.4 Soil profile in Tobimeita, Kendari, South Sulawesi, Indonesia (Okazaki 1995)

Profile B (Sago forest, potential acid sulfate soil)
0–7 cm, A, surface horizon, very yellowish brown (10 YR 5/5), moist, coarse sand, structureless, few medium and fine weed roots, pH 7.8, EC 0.30 mS/cm, clear smooth boundary to
7–35 cm, B1, grayish olive (5Y 5/2), moist, coarse sand, structureless, few organic debris with original shape and decomposed shape, pH 6.5, EC 0.32 mS/cm, clear smooth boundary to
35–70 cm, B2, brownish black (2.5 YR 3/2) in matrix and black (2.5 Y 2/1), wet, silty clay, structureless, common medium and fine sago roots, very sticky, plastic, pH 6.8, EC 0.32 mS/cm, gradual wavy boundary to
70– cm, dark grayish yellow (2.5 YR 5/2), wet, silty clay, structureless, sticky, pH 6.7, EC 0.35 mS/cm

Jalil and Bahari (1991) compared the starch yield of sago palm growing in plantations 0.5, 0.7, and 3.0 km from the seashore (soil pH: 3.3–3.8 in acid sulfate soils) and found that the starch yield was extremely high near the coast and lower in the inland plantations. In Thailand, Nozaki et al. (2004) compared the sago starch content and starch synthetic enzyme activity of sago palms growing in acid sulfate soils and Oxisols and found that the sago growth in acid sulfate soils was lower than that in Oxisols.

14.4 Peat Soils (Histosols)

In continental Southeast Asia under the tropical monsoon climate, rivers have complicated systems, while Southeast Asian islands under the tropical rainforest climate have shorter rivers than on the continents, which transport a small amount of sediments, resulting in the formation of peat soils called Histosols (Fibrists, Hemists, and Saprists) (Fig. 14.7). Trees, shrubs, and grasses that love water can thrive in the areas of high water table and tidal action. Dead plants are broken down usually by decomposers. However, the decomposition processes are inhibited in the areas of high groundwater. Plant residues accumulate to produce peat soils (Histosols), in which plant biomass production exceeds plant decomposition, regardless of temperature (Fig. 14.7).

Histosols are formed in the tropics in areas with high temperature and vigorous woody plant materials and are called *woody peats* (Okazaki 1998). Tropical peat soil is known to form a dome-shaped surface at the final stage of its development (Scott 1985) (Fig. 14.8). Tropical peat soils derived from woody materials in Southeast Asia exhibit strong to weak acidity and lack nutrient elements (Tie and Lim 1991; Yamaguchi et al. 1994). The constituent components in water flowing into tropical peat soils ensure the normal growth of sago palm (Yamaguchi et al. 1998). Sato et al. (1979) reported that the thicker the peat deposit in soil, the slower the sago palm grows and that the sago palm grew better in soil with a thinner peat layer and an underlying argillaceous deposit. In Sarawak 62% of sago palms are grown on Histosols, those with more than 150 cm of surface peats (Tie and Lim 1991). Kueh (1979, 1980, 1981, 1982, 1983) performed a cultivation study of sago palm in undrained tropical peat soils at Stapok in Sarawak and found a depression or no effect of nitrogen (ammonium sulfate) application on leaf production and no effect by P_2O_5 and K_2O, as their results, since 1976. Jaman (1983) found that NPK fertilizer application had no significant positive effect on the rate of leaf production of sago palm in the first year at Sungai Talau Peat Research Station. Jaman (1983, 1984, 1985) carried out experiments of fertilizer application, pruning, weeding,

Fig. 14.7 Soil profile of tropical peat in Sarawak

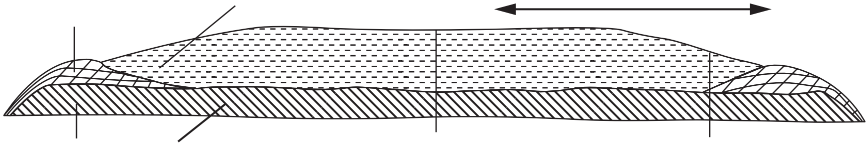

Fig. 14.8 Interrelations between landform units in tropical peat swamps wedged between 2 rivers (Scott (1985), cited from Anderson (1961))

seed germination, spacing, and intercropping related to girth, trunk height, and leaf production and reported that none of the NPK fertilizer application, pruning, weeding, seed germination, spacing, and intercropping had any significant positive effect on the annual leaf production rate of sago palms. Although in the 11th year of growth, trunk height in peat soil under minimal drainage at Stapok Station seemed to be increased by N application (Kueh 1987), there was no significant effect of N application on trunk height in the 13th year of growth (Kueh 1989, 1990, 1995). Kakuda et al. (2000) compared the nitrogen supply in peat and mineral soils. The amount of ammonium nitrogen released from peat soils through mineralization on the 50th day of incubation (100 days in case of transform at 25 °C) was approximately 5.8 mg/kg in Tebing Tinggi, Indonesia, and 4.7 mg/kg in Mukah, Sarawak. It is a property of peat soils that mineralization and nitrogen supply occur more readily as compared with mineral soils. The application of seven times the usual amount of N, P, K, Ca, Mg, Cu, Zn, Fe, and B provided a significant difference of petiole and sucker dry weight (Kakuda et al. 2005). However, no difference was found in other growth factors of sago palm.

The lack of any effect of nitrogen (N) application on sago palm growth is explained by the findings of the endophytes' activities on the N fixation (Shrestha et al. 2006, 2007). When sago palm easily becomes able to absorb N from soils, it does not require the N support by the endophytes. Accordingly it is concluded that the endophytes play an important role in sago palm growth without N application.

Beginning in 1986, Jaman and Jong (1986), Jong and Jaman (1987), Jong (1989, 1990), and Shoon et al. (1995) performed sago spacing (4.5, 7.5, 10.5, and 13.5 m) trials in peat soils in Sarawak and concluded that sago palm should be cultivated in a rectangular pattern of 12 × 8 m to facilitate maintenance work and farm management and suggested around 100 points per hectare. Traditional sago palm cultivation is carried out under minimal management, little sucker control, and no fertilization.

Groundwater level and subsidence related to drainage inhibit sago palm growth and yield of starch. Takaya (1983) and Shimoda and Power (1990) described that sago starch yield declined remarkably or even to zero in permanently submerged land. Flach et al. (1977) found in a sago seedling culture study that the rate of leaf emergence slowed under waterlogged conditions. Hashimoto et al. (2006) also reported that both the number of leaves and the diameter at breast height of sago palms growing in tropical peat soils with an average water table of 57–68 cm were smaller than those in the areas with a lower water table. Kakuda et al. (2015) revealed that sago palms grew better at 50 cm than at 90 cm of groundwater level. The groundwater level around the sago palm root zone is important for growth.

Sugawara (1979) proposed a 10,000 ha sago plantation on areas of tropical peat soils, which strongly required land reclamation and drainage for common tropical crop cultivation and its potential economic effect on Southeast Asian countries. Studies of the relationship between sago (*Metroxylon sagu* and *M. rumphii*) starch quality and soil types (shallow peat soils and mineral soils) in Sarawak were started by Lim and Loi (1987). However, thus far no results have been reported.

14.5 Other Entisols and Inceptisols

Soils eroded by rivers form sediments at the seashore at various rates. The soils along the Sepik River of Papua New Guinea are heavy clays high in organic matter and only flooded seasonally by the Sepik (Holmes and Newcombe 1980). Periodic flooding with water high in mineral elements should provide all of the nutrients required for optimum sago palm growth. Furthermore, Shimoda and Power (1990) reported that the soils of swampy areas in the Sepik River consisted of Hydraquents, Fluvaquents, and in part Histosols, which are poorly drained soils. Shimoda (2000) found the peat horizon at about 1 m depth in a Hydraquent profile. The formation of peat horizons and alluvial materials sedimentation has produced the sago-growing areas in the islands of Southeast Asia.

In Panay, Leyte, Cebu, and Mindanao, Philippines, the habitats of sago palm are predominantly located in Entisols and Inceptisols with periodic flooding and continuous water flow, from 0 to 700 m above sea level (Okazaki and Toyota 2003, 2004). The sago palms in Entisols and Inceptisols grow relatively well, compared to their growth on Histosols mainly utilized for leaf roofing materials in the Philippines, although local people know well how to extract starch in the mature sago palms.

14.6 Comparison of Sago Palm Growth Between on Inceptisols and Histosols

At the same growing stage, a comparison of sago palm has shown that the starch yield per trunk of the sago palm planted in deep peat soils is only 23 % of those planted in mineral soils (Jong and Flach 1995). Okazaki (2012) reported in a long-term growth study that the trunk weights of sago palm growing in Inceptisols of the Philippines and Indonesia at the different stages were larger than those in Histosols

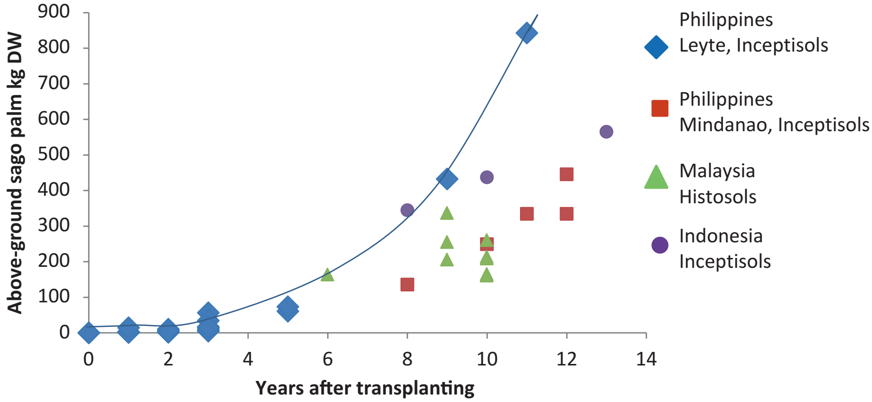

Fig. 14.9 Difference on biomass (above-ground) of sago palm growing in Inceptisols and Histosols (Okazaki 2012)

of Malaysia (Fig. 14.9). It is concluded that the sago palm growth and starch yield depend on the physicochemical soil characteristics.

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