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Nutrient Accumulation in Plant Tissues of Sago Palm in the Rosette Stage at Different Levels of Soil pH in South Thailand

Ornprapa Anugoolprasert[1], Shina Kinoshita[1], Wikanya Prathumyot[2], Preuk Chutimanukul[1], Somchai Chakhatrakan[3] and Hiroshi Ehara[1,*]

[1] Graduate School of Bioresources, Mie University, 1577 Kurimamachiya-cho, Tsu 514-8507, Japan.

[2] Faculty of Agricultural Technology, Rambhai Barni Rajabhat University, Chantaburi 22000, Thailand.

[3] Faculty of Science and Technology, Thammasat University, Pathumthani 12120, Thailand.

*Corresponding author: H. Ehara (ehara@bio.mie-u.ac.jp, fax: +81-59-231-9495).

Abstract Three young sago palms were collected at each sampling site from three locations in South Thailand to investigate the nutrient accumulation in plant tissues of sago palm in the rosette stage with no trunk formation grown at different levels of soil pH. The tendency in the case of Mg^{2+} concentration was displayed a significantly higher concentration in the whole plants of sago palm grown at the neutral pH soil (site 1) than those at the low pH soil (sites 2 and 3), which was similarly to that observed from soil sampled. Contrarily, the N and P concentrations in the whole plants of sago palm grown at the low pH soil (sites 2 and 3) were significantly higher than those at the neutral pH soil (site 1), although there were no differences in the available P and N in the soils at the three sampling sites. In addition, the effect of the difference in soil pH between the neutral pH soil (site 1) and the low pH soil (sites 2 and 3) on the K^+ and Ca^{2+} concentrations in the whole plants were indistinct. It is likely that sago palm grown at the low pH soil (sites 2 and 3) could maintain the uptake of macronutrients, which may be one of the major reasons that sago palm can adapt to growth in extremely acidic conditions. Furthermore, sago palms at the three sampling sites tended to store a higher Al^{3+} concentration in the cortex of adventitious roots than in other parts, such as the leaflet, and a similar tendency was observed for the accumulation of SO_4^{2-} and Na^+ in the plant tissues. It was, therefore, assumed that sago palm grown under any conditions of soil pH might exhibit an avoidance mechanism to restrict the distribution of any excess of undesirable nutrients in plant tissues, which may account for the ability of sago palm to grow in a range of soil pH from 4.3 to 7.0 in natural conditions.

Key words: nutrient concentration, sago palm, soil pH, South Thailand

タイ南部の異なる土壌pH条件下におけるロゼット期サゴヤシの養分蓄積

Ornprapa Anugoolprasert[1]・木下詩菜[1]・Wikanya Prathumyot[2]・Preuk Chutimanukul[1]・Somchai Chakhatrakan[3]・江原　宏[1]

[1] 三重大学大学院生物資源学研究科　〒514-8507　三重県津市栗真町屋町1577

[2] Faculty of Agricultural Technology, Rambhai Barni Rajabhat University, Chantaburi 22000, Thailand

[3] Faculty of Science and Technology, Thammasat University, Pathumthani 12120, Thailand

要約　異なる土壌pH条件で生育した幹立ち前のサゴヤシの養分蓄積を調査するため，タイ南部において土壌環境の異なる3ヶ所からロゼット期にあるサゴヤシ樹を3個体ずつ採取した．個体全体の植物組織中のマグネシウム濃度は，土壌pHが中性であったサイト1に生育する個体が酸性条件のサイト

2およびサイト3の個体よりも高く，土壌中の交換性マグネシウム含量も同様にサイト1で高かった．これに対し，全窒素とリンの植物体中の濃度はサイト1よりも土壌pHが低いサイト2とサイト3の方が高い結果であったが，土壌中の全窒素，有効態リン酸含量はサイト間で大きな差異はみられなかった．一方，植物体中のカリウムとカルシウム濃度には，土壌pHによる影響は認められず，このことがサゴヤシが強酸性条件にも適応できる主たる要因の一つと考えられた．さらに，いずれのサイトにおいても，不定根の皮層におけるアルミニウム濃度が葉鞘など他の部位に比べて高く，また，硫酸やナトリウム濃度も同様の傾向にあった．これらのことから，サゴヤシは体内での過剰な有害成分の移行を制限するメカニズムを有しており，それによって土壌pH4.3から中性の7.0と幅広い条件で生育できるものと考えられた．

キーワード：サゴヤシ，土壌pH，南タイ，養分濃度

Introduction

Recently, land and population crises have become serious issues around the world (Yanbuaban et al. 2007). Human activities have increased in magnitude and have begun to extend toward the coastal lowland areas, where peat swamps are widespread (Okubo et al. 2003). However, peat swamp soil is classified as having a very low potential for agriculture because of its physical and chemical properties, such as a high groundwater level and low nutrient content. In addition, most of these soils are highly acidic and generally contain highly exchangeable Al, in which almost no other crops grow without soil improvement (Osaki et al. 1998). Thus, actions to find new plant resources for future land uses are needed (Okubo et al. 2003).

Sago palm that stores large quantities of starch in its trunk is distributed in Southeast Asia, including South Thailand. This palm is one of the dominant species in tropical swampy and peaty soils and can grow in widely adverse conditions, such as acidic or saline-effected conditions. Flach and Schuiling (1989) reported that sago palm can be exploited without harmful effects on the existing ecological pattern and is really adapted to the humid tropical peat swamp. Considering the specific characteristics of sago palm, the efficient use of carbohydrates from sago palm is currently expected, followed by an anticipated increase in utilization from the viewpoint of land development in swampy areas. Since sago palm is distributed even in brackish water areas near the coast and peaty areas where the strong acidic soil reaction is usually observed, it is considered that sago palm can grow in a widely different soil pH. In general, the nutrients in soil are strongly affected by soil pH due to interaction between soil particles and nutrients in fact the availability of various nutrients has been determined depending on a function of soil pH. Beside, the soil pH generally affects the plant growth through the increase or decrease in the nutrient uptake and the effects of soil pH on the plant growth are complex because the change in content varies with the individual nutrient. Yamamoto et al. (2003) reported that the growth and starch yield of sago palm grown in deep peaty soil were comparatively smaller than those in mineral soil, which soil pH of deep peaty soil usually lower than those of mineral soil. Therefore, it can be speculated that the growth and nutrient uptake of sago palm may be affected by the soil pH. In addition, Yamamoto (1996) and Yamaguchi et al. (1997) suggested that the duration from establishment of a young sago palm to the beginning of trunk formation was closely related to the soil properties. Thus, in this study, we conducted plant sampling of young sago palm plants in the rosette stage and the nutrient concentrations in plant tissues were analyzed to make clear the nutrient uptake and translocation in plant body of young sago palm grown at three different sites in South Thailand where the soil pH was differed.

Materials and Methods

1. Study sites

Young sago palms from the small clumps with no trunk formation in the rosette stage were sampled at the three sites of the natural sago palm growing-area in South Thailand from 30 January to 5 February, 2010 (Fig. 1). The site 1 was in Ban Kaokok, Tambon Tongnien, Khonom District, Nakhon Si Thammarat Province (9º16'22.14"N, 99º47'36.74"E). The sites 2 and 3 were in Rattaphum District, Songkhla Province (site 2: Ban Thachamuang, Tambon Thachamuang, 7º07'25.22"N, 100º14'06.36"E; site 3: Phetkasem Road, Tambon Kamphangphet, 7º08'01.89"N, 100º15'20.17"E). The mean annual temperature in 2010 was approximately 27.6ºC in Nakhon Si Thammarat Province and 28.2ºC in Songkhla Province recorded at the nearest meteorological station of Thai meteorological department. The sites 1 and 3 located beside the canal, these sites were poorly drained and swampy. Contrarily, the site 2 where located near the residence of the villagers was well drained and comparatively dry.

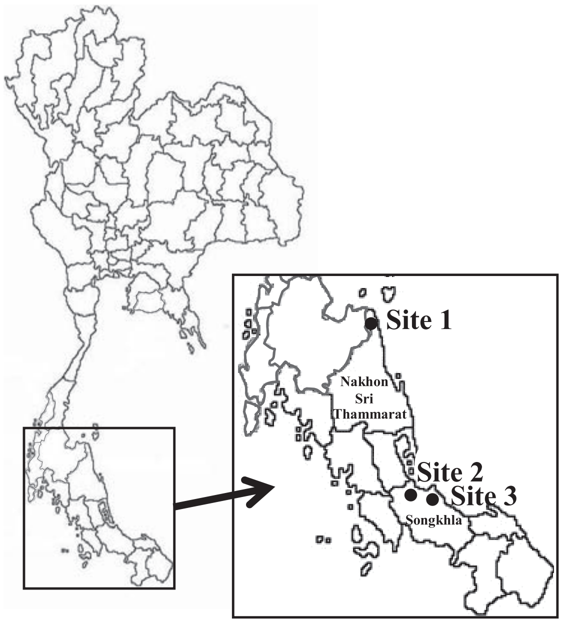

Fig. 1. Research area and sampling site distributed in South Thailand.

2. Soil physicochemical analysis

Soil samples were collected from a depth of 0-20 cm at each site. Then, the soil samples were air-dried for 4 days at room temperature and prepared to analyze the soil physical and chemical property by sieving through a 2 mm mesh. The soil pH, soil texture, organic matter, and nutrient contents in the soils were determined. Soil pH was measured at a soil : water ratio of 1 : 1 (w v^{-1}) by a pH meter. Total soil organic matter was measured by wet oxidation (Walkley and Black 1934). The soil texture was determined by the percentage of sand, silt and clay, which the percentage of each particle type was determined using the hydrometer method. The total N concentration was measured by the semi-micro Kjeldahl digestion procedure. The amount of available P was determined by the Bray II method. The exchangeable K, Ca, Mg and Na were extracted with 1N ammonium acetate (NH_4OAc) solution (pH 7.0) and extractable Al was extracted with 1N KCl. All exchangeable cations and extractable Al were determined by atomic absorption spectrophotometer (170-30 AA, Hitachi, Japan). The extractable SO_4 was extracted with 0.08M $Ca(H_2PO_4)_2 \cdot H_2O$ and analyzed using the turbidimetric method.

3. Plant sampling and analysis of nutrient concentration in plant tissues

Three young sago palms were selected from each site and were felled. After felling, the growth parameters including the plant height, number of the living leaves, and number of leaflets of the third leaf position from the top were measured. The SPAD value (SPAD-502, Minolta, Japan) which has a positive correlation data with chlorophyll content per unit leaf area (Uddling et al. 2007) was measured at each leaf of the samples. From each plant, the third leaf from the top, unexpanded leaf (a needle-like leaf) and adventitious roots were sampled. The third leaf was separated into four parts: leaflets, rachis, petiole and leaf sheath. The adventitious root was divided into stele and cortex (epidermis, exodermis, suberized sclerenchyma cell and cortex), which were classified according to the method of Nitta et al. (2002). The separated samples were dried in an oven at 80ºC for 72 hours to measure the dry weight and then ground into powder in order to analyze the nutrient concentrations. The ground samples were reduced to ash in a furnace and extracted with 1.0N HNO_3, and then the cation (K^+, Ca^{2+}, Mg^{2+} and Na^+) and anion (SO_4^{2-}) concentrations were determined using a high-performance liquid chromatography (HPLC) method with a conductivity detector (IC-C3 and IC-GA1, CDD-6A, Shimadzu, Japan). The concentration of P was evaluated by atomic absorption spectrophotometry. The total N concentration was determined by the semi-micro Kjeldahl method after the plant tissues were decomposed by a sulfuric acid. The Al^{3+} concentration was determined calorimetrically by the aluminon method.

Table 1. Characteristics of the physical and chemical properties of soil samples at the three sampling sites.

Soil properties	Sampling site		
	Site 1	Site 2	Site 3
pH (H_2O)	7.0	4.4	4.3
Liming ($CaCO_3$ kg ha^{-1})	-	5881.3	6718.8
Organic matter (g kg^{-1})	118.7	19.1	43.5
Soil texture	Clay	Loam	Clay
Sand (%)	33.0	31.0	23.0
Silt (%)	16.0	44.0	34.0
Clay (%)	51.0	25.0	43.0
Total N (g kg^{-1})	1.5	0.9	2.0
Avail. P (mg kg^{-1})	4.0	5.0	8.0
Exch. K (mg kg^{-1})	90.0	50.0	80.0
Exch. Ca (mg kg^{-1})	3196.0	196.0	716.0
Exch. Mg (mg kg^{-1})	680.0	40.0	90.0
Extract. Al (mg kg^{-1})	4.5	135.0	145.0
Extract. SO_4 (mg S kg^{-1})	115.6	6.2	21.9
Exch. Na (mg kg^{-1})	835.0	74.0	86.0

The statistical difference of the data was determined using NCSS 2001 (Number Cruncher Statistical Systems). The effect of different levels of soil pH was determined by one-way ANOVA (analysis of variance), and the differences among the mean values of the three sampling sites were determined using the Tukey-Kramer test.

Results and Discussion

1. Soil physicochemical properties

The physical and chemical properties of soil samples at the three sampling sites are shown in Table 1. The main particles of the soils at sites 1 and 3 were clay particles (clay texture), while those at site 2 were silt particles (loam texture). The organic matter content of the soils at sites 1 and 3 was higher than that at site 2. These results might be due to year-round or several months of waterlogged conditions at sites 1 and 3, which is related to the lower decomposition in the soils at those sites rather than in the drained soil at site 2. The soil at site 1 had a neutral pH of 7.0, while the soils at sites 2 and 3 had an extremely acid pH of 4.3 and 4.4, respectively. There have been several reports on the pH of tropical peat soil in a sago palm plantation, such as in Riau or Sarawak, where the pH ranged from pH 3.3 to pH 4.7 (Purwanto et al. 2002, Kawahigashi et al. 2003, Miyamoto et al. 2009). From the results of the current study, it was confirmed that sago palm grows in a widely different soil pH range from 4.3 to 7.0 under natural conditions in Thailand.

Almost all the concentrations of soil nutrients, such as those responsible for salinization (Na, Ca, and Mg) and extractable SO_4, were higher in the soil at site 1 (pH 7.0), followed by the soils at site 3 (pH 4.3) and site 2 (pH 4.4) (Table 1). On the other hand, the Al concentration was higher in the soils at sites 2 and 3 than in that at site 1. A tendency toward a higher Al concentration in the low pH soil than in the neutral pH soil was in agreement with that reported by Adams and Moore (1983), which suggests that the decrease in soil pH increased the amount of Al concentration in the soil solutions. According to Brady and Weil (2002), Al is a major constituent of most soil minerals, including clay. Although a low pH is defined as a high concentration of H^+ ions, Al also plays a major role in soil acidity. When H^+ ions are adsorbed on a clay surface, they do not usually remain as exchangeable cations for a long time but, instead, attack the structure of the minerals, releasing Al^{3+} ions in the process. In addition, the Al concentration in soil at the three sampling sites, 5-145 mg kg^{-1}, tended to be higher than the values reported for the peat soil of the sago palm cultivation in Sarawak, Malaysia, 5-14 mg kg^{-1} (Jong and Flach 1995).

The concentrations of N, P, and K, the essential macronutrients, were at almost the same low level at all the sampling sites (Table 1). A tendency toward poor macronutrient at the current sampling sites was in agreement with the report of Kawahigashi et al. (2003), suggesting that a deficiency in the nutritional condition is common among peat soils, especially strongly acid peat soil, and few plants survive in such adverse conditions.

2. Nutrient concentrations in different plant parts

Table 2 shows the size of young sago palms in the rosette stage grown under natural conditions at the three sampling sites. In the current study, all the young sago palms from three locations in South Thailand belonged to a non-spiny type. The average length of three sago palms from sites 1, 2, and 3 were 3.0, 5.0, and 3.9 m, respectively. The number of living leaves did not differ distinctively among the three sampling sites, being approximately 5-7. In the current study, the SPAD value of the leaflet from sites 2 and 3 tended to be higher than that from site 1. These results suggest that sago palm would show preferable growth under acid (sites 2 and 3) than neutral soil pH (site 1) conditions. The ages of the plant samples under natural conditions were unknown, and more data are thus necessary. Even so, the finding is noteworthy. The results of this study were similar to those obtained from observations of high level acidity tolerance for lowland rice, which had lower yields with a pH 6.0 treatment than with low pH treatments ranging from pH 3.5 to pH 5.0 (Thawornwong and Diest 1974). An experimental study on the comparison of the growth of sago palm under acid and neutral soil conditions will be conducted in the future.

The nutrient concentrations in different plant parts and whole plants of sago palm from the three sampling sites are shown in Tables 3 and 4. The N and P concentrations in all the plant parts of sago palm from sites 2 and 3 tended to be higher than those from site 1. Beside, the N and P concentrations in the whole plants of sago palm from sites 2 and 3 were significantly higher than that from site 1 (Table 4), although the available P and total N in the soils did not differ among the three sampling sites (Table 1). Probably, the comparatively higher P and N uptake of sago palm under low pH conditions (sites 2 and 3) may be an important factor to explain the acid resistance of sago palm. Furthermore, the N concentration in the leaflet was significantly higher than that in other parts, while the P concentration in different plant parts of sago palms at all the sampling sites tended to be higher in the unexpanded leaf than in other parts (Table 3). This tendency toward a higher concentration of N in the leaflet and P in the unexpanded leaf than in other parts was in agreement with the experimental study reported by Prathumyot et al. (2011). The K^+ concentration was significantly higher in the lower (petiole, leaf sheath and root) than the higher (leaflet) parts (Table 3), which was in agreement with the findings previously reported

Table 2. Young sago palms in the rosette stage grown under natural conditions at the three sampling sites.

Sampling site	Plant length (m)	Number of living leaves	Number of leaflets of the third leaf from the top	SPAD
Site 1	3.0	6.7	25.3	54.0 b
Site 2	5.0	5.3	53.7	64.8 ab
Site 3	3.9	7.3	48.0	67.2 a

Means followed by different letters within a column are significantly different at the 0.05 level by the Tukey-Kramer test (n=3).

Table 3. Nutrient concentrations in different plant parts of young sago palms grown under natural conditions at the three sampling sites.

Plant part	Sampling site	Nutrient concentration N (mg g^{-1})	P (mg g^{-1})	K^+ (μmol g^{-1})	Ca^{2+} (μmol g^{-1})	Mg^{2+} (μmol g^{-1})	Al^{3+} (μmol g^{-1})	SO_4^{2-} (μmol g^{-1})	Na^+ (μmol g^{-1})
Leaflet	Site 1	8.0 cA	1.0 cAB	177.6 aD	45.3 aB	49.6 aA	9.5 aB	28.2 aC	13.1 aC
	Site 2	14.0 bA	2.4 bBC	172.6 aC	31.5 aBC	32.5 bBC	10.8 aB	27.5 aA	4.3 bD
	Site 3	15.8 aA	3.1 aA	175.3 aC	42.8 aB	27.8 bCD	12.2 aB	29.5 aA	9.5 aB
Unexpanded leaf *	Site 1	7.7	1.3	518.8	31.7	49.9	8.7	23.0	14.1
	Site 2	11.7	6.1	344.6	28.5	28.3	10.5	13.0	5.8
	Site 3	12.0	7.0	496.9	40.8	31.9	13.9	20.9	10.1
Rachis	Site 1	2.7 bB	1.1 bA	531.3 aC	38.5 aB	48.4 aA	13.2 aB	37.3 aBC	18.7 aC
	Site 2	4.2 abBC	2.8 aAB	343.3 bBC	33.0 aB	22.1 bC	12.8 aB	22.4 bA	6.9 cD
	Site 3	5.3 aBC	3.1 aA	468.2 abB	37.1 aBC	29.7 bCD	13.4 aB	16.9 bB	10.9 bB
Petiole	Site 1	2.3 bB	0.8 bABC	570.4 aC	40.6 aB	48.5 aA	10.2 aB	37.2 aBC	28.7 aC
	Site 2	3.4 abC	3.8 aA	436.2 bB	34.7 aB	31.3 bBC	11.2 aB	7.2 bB	10.7 bC
	Site 3	4.7 aBC	4.1 aA	595.7 aAB	43.3 aB	39.3 abBC	12.0 aB	8.7 bC	12.6 bB
Leaf sheath	Site 1	3.5 aB	0.6 bBC	1084.6 aB	60.5 aA	49.9 aA	12.2 aB	23.7 aC	76.4 aB
	Site 2	3.4 aC	2.9 aAB	703.6 bA	43.3 bA	45.2 aAB	12.0 aB	6.9 bB	22.4 bB
	Site 3	4.1 aC	3.1 aA	732.6 bA	59.7 aA	48.9 aB	12.6 aB	8.5 bC	32.8 bA
Stele of adventitious root	Site 1	2.3 bB	0.4 bC	314.9 abCD	24.5 aC	48.3 aA	10.0 aB	59.8 aB	97.5 aB
	Site 2	5.9 aB	1.2 aC	395.1 aB	8.9 bD	18.6 bC	9.8 aB	11.0 bB	30.1 bAB
	Site 3	5.5 aBC	0.9 aB	201.8 bBC	9.5 bD	14.8 bD	9.8 aB	3.1 cD	32.7 bA
Cortex of adventitious root	Site 1	3.0 bB	0.9 bAB	1464.3 aA	34.4 aBC	60.4 bA	22.1 bA	187.3 aA	446.4 aA
	Site 2	6.9 aB	1.7 aBC	453.9 bB	25.5 aC	56.1 bA	28.1 aA	25.3 bA	36.5 bA
	Site 3	6.3 aB	1.0 bB	331.2 bBC	32.2 aC	74.7 aA	38.0 aA	27.3 bA	38.3 bA

Means followed by different letters are significantly different at the 0.05 level by the Tukey-Kramer test (n=3; *: data of the unexpanded leaf at the three sampling sites was from 2 plants). Small letter indicates comparison among the sampling sites in each plant parts. Capital letter indicates comparison among the plant tissues under each sampling site.

Table 4. Nutrient concentrations in whole plants of young sago palms grown under natural conditions at the three sampling sites.

Nutrient concentration	Sampling site Site 1	Site 2	Site 3
N (mg g^{-1})	3.5 b	7.1 a	7.7 a
P (mg g^{-1})	0.9 b	3.0 a	3.3 a
K^+ (μmol g^{-1})	546.0 a	415.3 b	466.1 ab
Ca^{2+} (μmol g^{-1})	37.3 ab	35.0 b	47.6 a
Mg^{2+} (μmol g^{-1})	52.2 a	34.7 b	38.1 b
Al^{3+} (μmol g^{-1})	13.0 a	14.8 a	15.8 a
SO_4^{2-} (μmol g^{-1})	61.1 a	21.4 b	16.5 b
Na^+ (μmol g^{-1})	124.3 a	17.4 b	21.0 b

Means followed by different letters are significantly different at the 0.05 level by the Tukey-Kramer test among the sampling sites (n=3).

(Matsumoto et al. 1998; Ehara et al. 2006; Prathumyot et al. 2011). In addition, the K^+ concentration in almost all the plant parts and whole plants tended to be higher in sago palm from site 1, followed by that from sites 3 and 2 (Table 4), which had a tendency similar to that observed in the results of soils at the three sampling sites (Table 1). However, the effect of the difference in soil pH between the neutral pH soil (site 1) and the low pH soil (sites 2 and 3) on the K^+ concentration was significant only in the case of the leaf sheath and cortex of adventitious root (Table 3). From the current results of macronutrients (N, P and K) in plant tissues, it is likely that sago palm grown at sites 2 and 3 could maintain or increase the uptake ability of macronutrients, which may be one of the major reasons that sago palm can adapt to growth in extremely acidic conditions.

The Ca^{2+} concentration in different plant parts of sago palms at all the sampling sites was significantly higher in the leaf sheath than in other parts, such as the leaflet or petiole (Table 3). In addition, the difference in the Ca^{2+} concentration in the whole plants between the neutral pH soil (site 1) and the low pH soil (sites 2 and 3) was not significant (Table 4), though the concentration of Ca in the soil at the three sampling sites was differed distinctively (Table 1). It was considered that the widely different soil pH in the range from pH 4.3 to pH 7.0 might not have a remarkable effect on the Ca^{2+} accumulation in the whole plant tissues. These results support the previous report of Matsumoto et al. (1998) suggesting that sago palm has some mechanism to remobilize Ca from old to new leaves, which may account for the constant accumulation of Ca in plant tissues, especially in the leaves, during growth under natural conditions.

The Mg^{2+} concentration in almost all the plant parts of sago palm from sites 2 and 3 tended to be lower than that from site 1 (Table 3), which tended to be similar to that observed from soil sampled (Table 1). Beside, the Mg^{2+} concentration in the whole plants of sago palm from site 1 was significantly higher than that from sites 2 and 3 (Table 4). However, the difference in Mg^{2+} concentration in the plant tissues was smaller than that in the soil among the three sampling sites (Tables 1 and 4). From site 1, the Mg^{2+} concentration tended to be the same level in all the plant parts, while the Mg^{2+} concentration in different parts of sago palm from sites 2 and 3 tended to be higher in the lower parts, especially the cortex of adventitious root, than that in the higher parts, such as the leaflet (Table 3). This result indicated that the translocation of Mg^{2+} from the root to the top parts might be restricted by the low pH conditions. According to Wu and Rebeiz (1985), absorbed Mg and N are important structural components located in the center of chlorophyll, as could be estimated from the result of the SPAD value of the leaflet in the current study. The higher chlorophyll production (higher SPAD value) of sago palm under low pH conditions (sites 2 and 3) could be attributed to the comparatively higher N accumulation in the leaflets, although the Mg^{2+} concentration in the leaflet of sago palm under low pH conditions was lower than those under neutral pH conditions (site 1).

The Al^{3+} concentration in almost all the plant parts and whole plants, except the cortex of adventitious root, did not display any significant differences among the sampling sites (Tables 3 and 4), although the Al concentration in the soils at site 1 was apparently lower than that at sites 2 and 3 (Table 1). In addition, the concentration of Al^{3+} in the higher plant parts was not very high in any sampling sites, whereas sago palm at all sampling sites tended to store a higher Al^{3+} concentration in the cortex of adventitious roots than in other parts (Table 3). It was considered that sago palm might prevent the excess $Al3^{+}$ influx at the cells between the cortex and stele, namely, the endodermis. However, Rasmussen (1968) reported that the concentration of Al was the highest at the surface of the root cap and steadily decreased toward the center of the corn root, and, furthermore, suggested that the epidermal layer of the root could obstruct the Al movement into the cortex and conductive tissues. Therefore, the observation of the localization and distribution of Al in the plant tissues of sago palm will be undertaken in our future research.

The SO_4^{2-} concentration in almost all the plant parts and whole plants of sago palm from site 1 was significantly higher than that from sites 2 and 3 (Tables 3 and 4), which a significant difference was clearly exposed in the cortex of adventitious root (Table 1). The SO_4^{2-} concentration in different plant parts of sago palm from site 1 was significantly higher in the cortex of adventitious root than that in other parts. There are several reports concerned with sulfate accumulation, suggesting that sulfate is generally regarded as an immobile element and its accumulation in the root zone is a frequent phenomenon in various plant species (Sunarpi and Anderson 1996, Kowalska 2004, Van der Welle et al. 2007). Nevertheless, this tendency toward a higher SO_4^{2-} concentration in the cortex of adventitious root than in other parts was not observed in sago palm from sites 2 and 3, which may be attributed to the relatively small amount of SO_4^{2-} concentration in the soils at both sampling sites compared with that in the soils at site 1. In addition, the SO_4^{2-} concentration in soil at the three sampling sites was in the range of 6 to 116 mg S kg^{-1}. According to Kyuma (2003), the SO_4^{2-} concentration in some representative acid sulfate soil and non-acid sulfate soil in the Bangkok plain for rice cultivation in Thailand was in the range of 181 to 5,235 mg S kg^{-1}. It is likely that the SO_4^{2-} concentration in the soils from the current sampling sites, especially the soils from sites 2 and 3 (6 and 22 mg S kg^{-1}, respectively), was comparatively lower than that from a former report.

The Na^+ concentration in the whole plants and almost all the plant parts, except the leaflet, were significantly higher in sago palm from site 1 than that from sites 2 and 3 (Tables 3 and 4), which tended to be similar to that observed in the result of soils among the three sampling sites. Beside, the Na^+ concentration in the soil from site 1 was 835 mg kg^{-1} or about 0.08% NaCl that was 10 times higher than the value in the soil from sites 2 and 3 (Table 1). Prathomyot et al. (2011) reported that the absorption of macronutrients (N and P) by sago palm was not inhibited by salt stress even under 1.3% (224 mM) NaCl, although the chlorophyll production was depressed. Based on these findings, it was considered that the Na^+ concentration in the soil (0.08% NaCl) from site 1 in the current study might not affect the macronutrients (N and P) of sago palm from site 1 (neutral pH soil). In this study, we found the significant difference in the N and P concentrations in the whole plant tissues among the three sampling sites, the value were higher in low pH condition (sites 2 and 3) rather than in neutral pH condition (site 1). Therefore, at least we will able to say sago palm grown at comparatively low pH soil showed the higher accumulation of N and P than that at the neutral pH soil condition in this study. However, the concentration of Na^+ in the soil from site 1 in this study might cause to delay the chlorophyll production, which may account for declining the SPAD value of sago palm from site 1. Nevertheless, Prathomyot et al. (2011) suggested that the chlorophyll concentration could increase up to high level over a comparatively long time because of there was no lack of materials, such as N and Mg, for the chlorophyll production, which may account for the ability to grow under salt stress even with a reduction of the growth rate. In addition, the Na^+ concentration in the cortex of adventitious root was higher than that in the other parts of sago palm at all the sampling sites (Table 3). This current results support the former findings of Ehara et al. (2008) showing that a dense distribution of Na was observed around the endodermis in the extension zone of the adventitious roots. Based on the finding of Prathumyot and Ehara (2010), the development of the Casparian strip located in the endodermal cell wall of the adventitious root of sago palm can be considered as an important mechanical factor relating to the avoidance mechanism for preventing the excess influx of Na^+ through an apoplastic partway into the stele and its translocation from root to shoot in sago palm.

Conclusion

The current study demonstrates some tendencies of the nutrient uptake and translocation in plant tissues of sago palm in its natural habitat, which were similar to the results of our experimental study in the laboratory (Ehara et al. 2008, Prathumyot et al. 2011). Based on the current results of macronutrients (N, P, K and Ca) in the plant tissues, it is likely that sago palm grown at sites 2 and 3, pH 4.4 and pH 4.3, respectively, could maintain or increase the uptake of macronutrients, which may be a major reason that sago palm can adapt to growth in strongly acidic soil in a natural habitat. Furthermore, sago palms at all the sampling sites tended to store a higher Al^{3+} concentration in the cortex of adventitious roots than in other parts, such as the leaflet, and a similar tendency was observed for the accumulation of SO_4^{2-} and Na^+ in plant tissues. It was, therefore, assumed that sago palm grown under any conditions of soil pH might exhibit an avoidance mechanism to prevent the excess influx of these nutrients in the plant tissues. The finding in our study strongly supports the prospect that sago palm, with its high adaptability to grow under widely different pH (pH 4.3 to pH 7.0), can be a useful crop for utilization from the viewpoint of land development in peatlands.

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