Growth Behavior of Sago Palm (Metroxylon sagu Rottb.) from Transplantation to Trunk Formation

Keita Nabeya¹, Satoshi Nakamura², Teiji Nakamura¹, Akihiro Fujii¹, Manabu Watanabe³, Takayuki Nakajima¹, Youji Nitta⁴ and Yusuke Goto¹

¹Graduate School of Agricultural Science, Tohoku University, Sendai 981-8555, Japan;
²School of Food, Agricultural and Environmental Sciences, Miyagi University, Sendai 982-0215, Japan;
³Field Science Center, Faculty of Agriculture, Iwate University, Sugo, Takizawa 020-0611, Japan;
⁴College of Agriculture, Ibaraki University, Ami 300-0393, Japan

Abstract: Because of the large amounts of starch accumulated in its trunk, the sago palm (Metroxylon sagu Rottb.) growing in tropical areas of Southeast Asia has received much attention as a starch crop mainly for use as an industrial raw material. Sago palm propagates generally by transplantation of suckers, but little agronomical knowledge is available for transplanted sucker growth. Our objectives are to clarify sago palm growth after transplantation and to assess the transition of stem growth from horizontal to vertical. The transplanted sucker stems elongate horizontally, creeping along the ground surface in the early growth stage. Subsequently, the stem elongation shifts gradually from horizontal to vertical. The creeping stem stands up, drawing a large arc and elongating vertically. The horizontal stem elongation stops at around 6.5 years after transplantation and the stem growth curve shows a sigmoidal curve. The stem growth stage of a transplanted sucker is divisible into three stages based on its elongation direction: the creeping growth stage, the trunk formation stage, and the trunk elongation stage. The creeping growth stage, which is the early growth stage after transplantation, is an important period because the standing positions of trunks are determined in the plant and in the sago palm garden. In the area we investigated, the transplanted suckers remained in the creeping growth stage for 4–5 years. They remained in the trunk formation stage for around 1.5 years. These suckers will probably be in a trunk elongation stage for 6–7 years.

Key words: Creeping growth, Growth stage, Metroxylon sagu Rottb., Sago palm, Transplanted sucker, Trunk formation.

Sago palm (Metroxylon sagu Rottb.) is an Arecaceae distributed in Southeast Asia and Melanesia, in countries such as Malaysia, Indonesia and Papua New Guinea, in a zone 10 degrees north and south of the equator (Flach, 1977; Nagato and Shimoda, 1979). It accumulates a large amount of starch in its trunk. Starch of about 290 kg can be harvested from a single trunk (Yamamoto, 2006). In regions where sago palms grow, sago starch has traditionally been used as food with taro, banana, and so on. However, rice is consumed recently as a staple food because of a change of diet, resulting in the gradual rejection of sago starch as a staple food (Takahashi and Hirao, 1992). Nevertheless, the sago palm has received much attention as a starch crop mainly for use as an industrial raw material because of its high starch productivity.

Currently, the demand for starch worldwide continues to increase because of additional demands for bio-ethanol production. In fact, the starch supply is expected to be insufficient to meet the predicted future demand because the production of major starch crops such as corn and cassava for industrial material is suppressed by competition with food production and limited fields to grow starch crops. Under these circumstances, starch production by sago palm is receiving much attention because large-scale production at plantations began in Indonesia recently. In addition, sago palm can grow on humid peat soil at plantations (Sato et al., 1979), suggesting the possibility of avoiding competition for farmland with other crops. Therefore, the expansion of production and development

Received 7 May 2014. Accepted 14 October 2014. Corresponding author: S. Nakamura (nakamurs@myu.ac.jp, fax +81-22-245-1278). This research was supported in part by a Grant-in-Aid for Scientific Research (No. 20405017) from the Ministry of Education, Culture, Sports, Science and Technology, Japan and by a grant for research abroad from Miyagi University, Japan.

Abbreviations: ebIN_n, the n-th (counted basipetally) internode; ebl_n, the n-th (counted basipetally) emerged leaf; ebN_n, the n-th (counted basipetally) node; YAT, year after transplantation.
of new farms are forecast for the future.

The first large-scale sago cultivation at a plantation was developed during the 1980s (Jong, 2010). Sago palm has been cultivated by individual farmers. Therefore, little scientific knowledge exists in relation to its growth and cultivation techniques. Both still depend strongly on each farmer’s experience. Sago palm can be propagated mainly by suckers, which are branches from the base of stem, raised as seedlings (Sato et al., 1979). The stem of the transplanted sucker elongates along the ground surface during the rosette stage. After several years, the stem elongates upward and forms a trunk. During the creeping growth, many suckers appear from the creeping stem. These suckers also creep and disperse from the transplanted position. Flach (1983) described a plant model by which the mother stem formed its trunk at the plant center without creeping growth; some suckers crept and formed trunks around the mother trunk. However, no such plants have been observed in sago palm gardens in Malaysia and Indonesia, in our investigation. This inconsistent observation is attributable to the difference between the cultivation of seedlings from seed and from transplanted suckers. The Flach plant model might be applicable to plants from seed, not from the transplanted suckers that are normally used for sago palm cultivation. For plants from seedlings, as an example, a mother stem was able to form a trunk without creeping growth. However, many suckers grew around the mother trunk. Under these circumstances, cultivation management could be difficult because cutting down the mother trunk would injure the suckers around the trunk at harvest. On the other hand, in transplant cultivation, transplanting suckers lying down with the stem creeping can be expected to maintain some distance between the stem and its derivative suckers and to avoid injuring them. In any case, neither growth of the seedling plant nor that of the transplanted plant has been elucidated from a crop science perspective.

The relation between the sago palm growth and the accumulation of starch in the trunk after trunk formation has been studied in detail (Jong and Flach, 1995; Yamamoto et al., 2003a, 2003b), but the growth behavior of transplanted suckers from transplantation to trunk formation has been only slightly reported because the harvested organ is the trunk in the latter half of life cycle. Investigating the growth of living plants when larger than a given size after transplanting is therefore difficult. Although the changes of growth parameters such as plant height and leaf emergence rates from transplantation to the trunk formation stage were reported by Irawan et al. (2012), there has been no report about the stem elongation from transplantation to the trunk elongation stage. Our objectives are to clarify the sago palm growth behavior, especially focusing on the creeping growth, after transplantation by monitoring the same plants in the field, and to clarify the transition of stem growth of transplanted suckers from horizontal to vertical growth.

**Materials and Methods**

This monitoring investigation was conducted in a sago palm garden in Mukah, Sarawak, Malaysia (02°56’31.4”N; 112°18’26.6”E). The spineless type of sago palm, which is widely cultivated in Sarawak, was used. Suckers collected from the mother stem were raised in a nursery using conventional methods. The sucker cut leaves were laid on a floating raft in pond. The bottom half of the sucker stem was soaked in water. The suckers were nursed for about 3 months (Fig. 1). Then, these suckers were transplanted in a plastic bag filled with soil, and were nursed for an additional 3 months (the nursery period to this point was 6 months). The suckers were then transplanted in a field on 2 September 2005 in the conventional way: the sucker stems were laid down on the ground with the new leaves upward. In this report, we designate the transplanted sucker as the main sucker.

The distances separating planting rows and plants were, respectively, 6 m and 5 m. Actually, the space between planting rows was 4.6 – 7.2 m (avg. 6.0 m). The space between plants was 2.9 – 7.1 m (avg. 5.1 m) considering the topography. The area occupied by one plant was 30.6 m² on average, and the plant density was 327 plants ha⁻¹. The cultivation management was conducted using local conventional methods without fertilizer application.

We arranged an experimental section (35 × 47 m) where 56 plants grew in the field and investigated the growth of 21 of these plants. Furthermore, we selected 6 plants with average growth from the 21 plants and investigated not only the number of leaves and the stem growth but also the stem formation in the trunk formation. In this study, we analyzed the growth of the 6 plants in detail. We recorded the stem length in the horizontal direction and the increase in leaf number once or twice a year as follows.

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**Fig. 1.** Nursery of suckers.
For recording of the stem length, first we stuck a glass fiber pole in the ground to touch the stem end of transplanted sucker, and established it as the reference point. The stem length in the creeping part was defined as the horizontal distance from the growth point judged by the appearance to the reference point. The elongation process of the stem in the creeping part was analyzed by using JMP statistical processing software. To determine the increase in the number of leaves, we marked the leaf position on the leaf sheath by a marker pen considering phyllotaxy based on a spear leaf (Jones, 1995), which was the youngest leaf recognized by appearance, at every investigation, and evaluated the increase in leaf number based on the spear leaf of a plant at 3.3 years after transplantation (YAT 3.3). For analysis of the increase in leaf number, we regarded the spear leaf as $\alpha$ at YAT 3.3. We designated the leaf position of the spear leaf as ebL 1 and counted the emerged leaf position basipetally (Nakamura et al., 2004). We counted node and internode position basipetally as well as the leaf position.

To elucidate the sago palm stem formation process, we investigated the stem in the creeping growth stage and after trunk formation stage. In the sago palm, since a leaf sheath, which is the lower part of the petiole, wraps around the trunk, an attached part of leaf sheath, namely, a leaf scar, appears to be a node after removal of the leaf sheath. Therefore, when we analyzed the stem elongation, we considered a leaf scar as a node and a part between adjacent nodes as an internode: the $n$-th node (ebN $n$) is the attached part of the $n$-th leaf (ebL $n$). The $n$-th internode (ebN $n$) is an internode between the $n$-th node (ebN $n$) and the $(n-1)$-th node (ebN $(n-1)$). Because the nodes are slightly warped, we presumed a flat nodal plane for stem formation analysis. We removed the leaf sheath from the trunk without damaging the trunk and recorded the internode length, the circumference of node and the angle of nodal plane to the ground.

As a sago palm grows, many suckers appear from the mother stem. For this report, we designate the sucker derived from the main sucker (MS) as the primary sucker (PS), and the sucker derived from PS as the secondary sucker (SS). We also called PS and SS derivative sucker (DS).

Results

1. **Main sucker growth**

A sago palm at YAT 1.0 is presented in Fig. 2a. The blue pole (△) shows the end of the stem of the main sucker: the reference point. The sucker stem crept in a straight line on the ground. The creeping direction was the same when the sucker was transplanted. In the main suckers, at about 1 year after transplantation, the length of the creeping part was about 25 cm. The plant height was about 1.5 m on average. Leaves emerged closely from the ground surface in a rosette-like fashion. At the base of the leaves, 1 – 3 primary suckers appeared and grew.

A sago palm at YAT 2.9 is depicted in Fig. 2b. Many derivative suckers form a thicket around the transplantation position. In the main sucker, the length of the creeping part was about 60 cm; the plant height was around 3.0 m. Emerging new leaves, attached in the form of a rosette, shifted with the stem elongation. Consequently, the main sucker growth point position was located at a slight distance from the group of derivative suckers around the transplanted position.

A sago palm at YAT 4.8 is portrayed in Fig. 2c. The length of the creeping part was about 130 cm. The plant height was about 5.0 m on average. This is the time for sucker-control, an important sago palm cultivation management practice, to be started. Sucker-control is done to thin out unnecessary derivative suckers to avoid overluxuriant growth. Fig. 2(c) shows a plant immediately after thinning out the derivative suckers which grew around the transplantation position.

A sago palm at YAT 5.8 is presented in Fig. 3a. The length of the creeping part of the main suckers was about 165 cm. The position where leaves were attached was higher than the ground surface. The trunk started to form under the position, which is called trunk formation. The creeping growth of the main sucker ceased at the time of trunk formation. The positions of the main sucker and its derivative suckers in this plant are shown from above in Fig. 3b. The dark green circle shows the main sucker (MS). Bright green circles show the derivative suckers (PS and SS) that would be kept alive until harvest. Black circles show the derivative suckers with leaves pruned by sucker-control. MS crept in a straight line from the transplanting position (△). In fact, PS-A, PS-B, and PS-C are the primary suckers derived from MS around 1 year after transplantation. Then they crept away from MS. Empirically, these suckers are expected to be harvested approximately 2 – 3 years after harvesting of MS. SS-A, is the secondary sucker derived from PS-A, and is expected to be harvested around 1 – 2 years after harvesting of PS-A, PS-B, and PS-C. Four remaining derivative suckers (PS-D, PS-E, SS-B, and SS-C) grew in the space created by the creeping growth of MS and PS-A, and of PS-B and PS-C. These suckers would be harvested approximately 2 – 3 years after harvesting of SSA.

2. **Creeping elongation**

The length of the creeping part and the main sucker elongation rate are depicted in Fig. 4. The creeping part length increased exponentially from transplantation to around 4 years thereafter, and gradually increased slowly. For this reason, the growth curve, which implied the horizontal elongation, was sigmoidal. The creeping part length was 1.62–2.05 m (avg. 1.81 m) in YAT 7.8.
The rate of horizontal stem elongation was approximated as a Richard function. The solid line (—) in Fig. 4 shows the approximate curve of the stem length. The equation is presented as follows.

\[ y = 1.82 - \frac{1.84}{1 + e^{0.61x-3.97}}^{4.66} \]  

(1)

In this equation, \( y \) represents the creeping stem length and \( x \) represents YAT. This approximation is differentiated with a set elongation rate. The dashed line (-----) in Fig. 4 shows the curve that represents the equation differentiated from equation (1). The equation is shown as follows.

\[ \frac{dy}{dx} = 5.28e^{0.61x-3.97} / (1 + e^{0.61x-3.97})^{5.66} \]  

(2)

The maximum elongation rate was estimated as 0.38 m per year at YAT 3.8.

3. **Increase in the leaf number on the main sucker**

The expanded leaf number and the increasing rate of leaf number after YAT 3.3 are portrayed in Fig. 5. The number of leaves increased during the 4.5 years from YAT.
3.3 to YAT 7.8 was 44.2. Consequently, it was inferred that about 10 leaves expand annually, or slightly less than 1 leaf per month. However, because the leaf number is represented by a natural number, the rate of increase in leaf number can depend on the relation between the timing of leaf emergence and the date the leaf number was recorded. Therefore, we approximated the leaf number to analyze the rate of increase in leaf number. The leaf number can be approximated linearly as

$$y = 9.63 \times x - 30.55$$ (3)

Therein, $y$ represents the leaf number and $x$ represents YAT. Equation (3) is differentiated and set up with the increase in leaf number rate as follows.

$$\frac{dy}{dx} = 9.63$$ (4)

Consequently, the results of linear regression suggest that 9.63 leaves can be expected to increase in a year, or 1 leaf every 38 days.

4. **Stem formation during creeping growth**

We dissected the plant at YAT 3.3 to investigate the creeping stem. In the main sucker of this plant, the length of the creeping part was about 70 cm. The plant had 15 green leaves including a spear leaf. The main sucker stem was cut at the base and the leaves were removed carefully (Fig. 6a). The stem was cut longitudinally along the center; and the inside was observed (Fig. 6b). In the longitudinal section of stem, morphological characteristics such as nodes were not recognized clearly. Representing the nodal planes, which were estimated as the positions of attached leaves, by dashed lines, the nodal planes lined up almost as parallel (Fig. 6b). The red solid line in this figure shows the position to which leaves were attached (Fig. 6c) to analyze the structure near the growth point in detail. The conical part in the center of Fig. 6c comprises leaves that had not yet emerged. Six immature leaves were recognized by the naked eye in this part.

Assuming the attached part of a spear leaf (ebL 1) as the node of ebN 1, the maximum diameter of the nodal plane was ebN 10. The nodal plane area increased constantly from ebN 3 to ebN 10. Regarding the internode length, the length increased from ebN 4 to ebN 6, which were internodes between ebN 3 and ebN 6. The length of internode below ebN 7 was almost constant. In the part presented in Fig. 6c, the area of the nodal plane increased exponentially toward the lower nodes, whereas the internode only elongated slightly. The area near the growth point was hollow.

5. **Stem formation in the trunk formation**

Initially during trunk formation, the horizontal creeping growth of the stem ceases and vertical elongation growth starts. We investigated how the stem growth changed from horizontal to vertical during trunk formation. Using the measured values of the position and node diameter in the plant in YAT 7.8 (Fig. 7a), after removing leaf sheathes from lower part of the main stem (trunk) carefully, a schematic diagram of the stem was created as presented in Fig. 7b as one example. The stems of other plants showed similar morphology. In Fig. 7b, the ellipses show nodes. The dots are the center of the node plane, which portrays the estimated position of the growth point. Following the dots from the base to upper corresponds to the course of the estimated growth point. During the trunk formation process, the growth point position shifted not only vertically but also horizontally. To analyze the shift of the growth point position, the position vector of the growth point from ebN $n$ to ebN $(n-1)$ was divided into the movement distance to horizontal ($X$) and to vertical ($Y$). When the ratio of $Y$ to $X$ is greater than 1.0, the lowest internode to satisfy this condition is defined as the border...
Fig. 6. Stem in the creeping growth at YAT 3.3. (a): Stem after removing leaves carefully. Bar = 10 cm. (b): Longitudinal section of the stem. The dashed line (----) shows the estimated position of the nodal planes from leaf bases. (c): The top of the stem. ebN 1 shows the attached position of a spear leaf (ebL 1).

Fig. 7. (a): A sago palm at YAT 7.8. The triangle denotes the transplanting position. The arrow indicates the position of the estimated growth point. (b): Diagram of the stem formation in the trunk formation. The ellipses show nodes. The dots represent the centers of the respective node planes, which show the estimated position of the growth point. The internode colored light brown is the border internode (BIN). Bar = 50 cm.
internode (BIN). The period when BIN elongated was defined as the onset of trunk formation.

Based on the BIN of each plant, the movement distance of growth point to horizontal and vertical on each internode position is presented in Fig. 8. The movement distances to horizontal were 3 – 4 cm around ebIN b (b indicates the internode position of BIN), but the distance decreased with higher internodes above ebIN (b-2). It was 0.5 cm in ebIN (b-13). The growth point position moved horizontally about 30 cm from ebIN b to ebIN (b-13). However, the movement distance to vertical was 2.1 cm at ebIN (b+2). The distance increased quickly with higher internodes. The distance to vertical was about 11 cm around ebIN (b-10), almost constant above ebIN (b-10).

The angle of nodal plane on each nodal position is presented in Fig. 9. For nodes below ebIN b, the angle to the ground was around 40°. In the nodes above ebIN b, the angle decreased by about 2.7° per node linearly. Accordingly, during the creeping growth, the nodal plane had an angle of about 40° to the ground. Each internode was aligned almost as parallel, but during the trunk formation, the nodal plane gradually became level with the ground.

Discussion

In cultivated sago palm, the main sucker and its derivative suckers grow in directions away from the transplanted position because derivative suckers (mostly primary suckers) that appeared in early growth crept away from the main sucker, in addition to the creeping growth of the main sucker. Consequently, the growth of plants investigated in this study differed from the plant model of sago palm presented by Flach (1983). This difference seems to be attributable to the plant model that used seedlings germinated from seeds, not transplanted suckers. In the transplant cultivation of sago palm, which is popular in sago palm plantations, a main transplanted sucker crept in early growth. For that reason, the transplanted plant can differ from the plant model by Flach.

The main sucker crept about 1.8 m horizontally from the transplanting position for 7.8 years. Its growth curve drew a sigmoidal curve. The elongation rate became the maximum at YAT 3.8. Therefore, it was not considered that sucker-control after the time at the maximum rate affected the time when the main sucker elongation rate as a stem decreased. At YAT 7.8, horizontal elongation of the main sucker stopped, and the main sucker formed a trunk and elongated vertically. The main sucker stem elongated about 30 cm horizontally above BIN. Consequently, the period during which trunk formation started might be the time when the length of the creeping part was about 1.5 m. The time was thought to be around YAT 5.0. Furthermore, the period during which the trunk formation started can also be estimated according to the number of emerged leaves. In this study, the period during which a specific leaf of the plant emerged was estimated because the leaf numbers of the plants were recorded at regular intervals. As presented in Fig. 6, designating the node with a spear leaf attached as ebN 1, the internodes from ebIN 4 to ebIN 6 elongated during the spear leaf emerging in the creeping stem before trunk formation. Regarding the rapidly elongating internode positions, the internodes from ebIN 1 to ebIN 4 reportedly elongated quickly when a spear leaf emerged in the stem after trunk formation (Watanabe et al., 2010). Consequently, when ebL n emerged as a spear leaf, the internodes from ebIN (n + 3) to ebIN (n + 5) elongated in the creeping stem before trunk formation; the internodes from ebIN n to ebIN (n + 5) elongated in the stem after trunk formation. According to the relation between the leaf emergence and the internode elongation before trunk formation, when ebL b elongates, corresponding to the internodes from ebIN (n + 3) to ebIN (n + 5), leaves through ebL (b-3) to ebL (b-5) emerge as a spear leaf. Using the recorded data of the leaf position and the internode position ‘b’ of each
plant investigated, we could estimate the period when ebIN elongated, resulting in that the period when ebIN elongated would be around YAT 4.7. This period almost corresponded with the period estimated from the data of the stem length in creeping part. Therefore, it was thought that the main sucker crept 1.5 m horizontally around YAT 5.0 and subsequently started the trunk formation and formed a trunk at a position 1.8 m distant from the transplantation position.

Fig. 10 portrays a diagram of a stem after trunk formation based on the internode lengths, as estimated from the stem elongation rate and the increasing rate of leaf number, and the state of stem in the creeping growth and in the trunk formation stage. The black solid line shows the part that was modified based on the measured value of the stem. The internode colored gray shows BIN. The trunk formation started from BIN. In the creeping stem, nodal planes aligned almost parallel. For a sucker in the early growth stage, with the size for transplanting, nodal planes are reportedly aligned as parallel (Watanabe et al., 2010). These results suggest that the sago palm stem was formed by the horizontal line of thin disciform internodes maintaining an angle during the creeping growth. After creeping growth, the stem elongation decreased horizontally and the elongation increased vertically at the trunk formation and the angle of nodal plane to the ground decreased gradually. Consequently, the internodes were piled up vertically, forming the trunk. Regarding the internode length, it was about 0.5 cm at the time of transplanting. It increased with stem elongation. Subsequently, it was about 4 cm immediately before trunk formation and around 11 cm after trunk formation.

Considering the results described above, the transplanted sago palm stem elongation is classifiable into the following three stages: (1) creeping growth, during which the stem elongates horizontally; (2) trunk formation, during which the stem elongation shifts from horizontal to vertical; (3) trunk elongation, when the stem elongates vertically. The creeping growth stage, which was the core in this study, was the period in which the part to which leaves are attached, like a rosette, moves from the transplanted position to be horizontal with stem elongation. In the trunk formation stage, whenever a leaf emerges, the horizontal stem elongation decreases. The vertical elongation increases, raising the creeping stem to draw a big arc, which becomes a trunk. In the trunk elongation stage, starch is accumulated in the trunk from the lower part. Therefore, the creeping growth stage early after transplantation is an extremely important period because the standing positions of trunks are determined in the plant and in the sago palm garden. Understanding the growth behavior during this period is expected to improve the cultivation technology of sago palm for sustainable starch production.

In the area we investigated, the main suckers remained in the creeping growth stage for 4 – 5 years and in the trunk formation stage for 1 – 1.5 years. In addition, the trunk will elongate for 6 – 7 years before harvesting of the
main suckers, which is expected to start in 2017, corresponding to 12 years after transplantation.

Acknowledgements

We are very grateful for the assistance of Mr. Smith and his family in Malaysia.

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