The Effects of Night Soil–Temperatures on Diurnal Changes in Carbohydrate Contents in Roots and Stems of Sweet Potatoes (*Ipomoea batatas* Poir.)

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Summary

Sweet potatoes (*Ipomoea batatas* Poir.) were field-grown or grown in boxes in which the soil temperature was kept at 20 °C (cool), 30 °C (heat), or ambient (control). Field-grown plants were dug at 5:00, 11:00, 17:00 and 23:00, weighed, then dried and then re-weighed. The total fresh weights per plant, sampled at the respective times, were : 7250 g, 7800 g, 10650 g, 7666 g. The dry samples of stems and roots were analyzed for soluble sugars and starch. Sucrose content in the stem that was 44.5 mg · g⁻¹ DW at 5:00 increased gradually to 72.0 mg · g⁻¹ DW by 23:00, whereas that in the roots increased from 60 mg · g⁻¹ DW at 5:00 and 11:00 to 70.5 mg · g⁻¹ DW and 82.2 mg · g⁻¹ DW at 17:00 and 23:00, respectively. Sucrose content in stems of plants grown at the cool plot at night was lower than that in the heat plot. The skin of the root was brilliant red in the control and cool plots, whereas it was almost pink in the heat plot. Root sucrose content was higher in the heat plot than in the cool plot; the starch level was inverse of that of sucrose. These results indicate that sucrose transported into the root is converted to starch mainly at night. As the conversion of sucrose to starch by low night soil–temperature is not suppressed, the excess is diverted to root growth and/or metabolized into anthocyanin resulting in highly colored red roots with high sugar and starch contents.

Key Words: anthocyanin, diurnal change, night soil–temperature, starch, sucrose, sweet potato.

Introduction

The important factors for grading fresh sweet potatoes (*Ipomoea batatas* Poir.) are skin color, sweet taste and texture. Red color formation on the root skin corresponds with high sugar and starch accumulation in the root (Kato and Nakayama, 1975), whereas the texture is closely related to high starch content in the root (Sakamoto, 1989). Sugar and starch content in the root at harvest is attributable to the daily accumulation which depends on whether the environmental conditions are favorable for photosynthesis. No research on the diurnal changes in the root has been published, as opposed to many papers on seasonal changes of sugar and starch content (Yoshida et al., 1970; Murata, 1970; Hozyo et al., 1971; Kokubu, 1973). As sucrose and starch in the root of sweet potatoes depends on the rate of sucrose transport from leaves via the stem, root growth and quality are greatly affected by sucrose content in the stem. Murata (1970) found that active starch accumulation in the root of sweet potatoes 80 to 110 days after planting, whereas Yoshida et al. (1970) showed that leaf and stem weights of sweet potatoes reach a maximum around the middle of August, indicating that roots

accumulate much photosynthates during the latter half of the growing period. However, Nisiuti (1948) had demonstrated that soil temperature is one of the important factors regulating root thickening of sweet potatoes, whereas Hasegawa and Yahiro (1957) reported that night soil–temperature had a remarkable influence on this process.

In this paper, we investigated the effects of different soil temperatures on the diurnal changes in the stem, and sugar and starch content in the root during the latter half of the root growing period.

Materials and Methods

Experiment 1. Diurnal changes of sugar content in the stem, and sugar and starch content in the field-grown root

The experiment was carried out in the field of the Experimental Farm of Ishikawa Agricultural College in 1999. As basal fertilizers, 11.1 kg of N, 24.8 kg of P₂O₅ and 21.6 kg of K₂O per 10 ares were applied to the field before planting. Nursery plants of sweet potatoes (*Ipomoea batatas* Poir.), cv. Kokei No. 14 were planted on 20 May. On 27 September, six whole plants were dug at 5:00 (before sunrise), 11:00 (during active photosynthesis), 17:00 (at dusk) and 23:00 (complete darkness). After the weights of leaves and stems, and tuberous

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roots were recorded, the roots were cut cross-wise at the center in round slices 1 cm thick, and dried first at 80 °C for a day and then at 60 °C for 3 days, and the contents of sucrose, glucose, fructose and starch were analyzed on the dry matter. The roots heavier than 50 g were regarded as tuberous roots. Two pieces of 10 cm-long stems just above the ground per stock were also collected and dried. After the dry matter obtained from the stem and root were pulverized, 200 mg of stem powder and 100 mg of root powder were extracted with hot 80% ethanol, brought to volume, and an aliquot of the extract applied to HPLC (Shim-pack SCR-101C, Shimadzu Co. Ltd.; column temperature, 80 °C) for sucrose, glucose and fructose analysis. The residues after sugar extraction were treated with perchloric acid and the resulting sugar content determined, using the anthrone-sulphuric acid method and expressed as starch.

Experiment 2. Effects of night soil-temperature on sugar content in the stem, and sugar and starch content in the root

The experiments were carried out in the greenhouse of the Experimental Farm of Ishikawa Agricultural College in 1999. Wooden boxes of 30 × 30 × 300 cm (W × D × L) were filled with a compost of one-third of paddy soil, one-third of sandy soil and one-third of barnyard manure, to which an equivalent of 11.1 kg of N, 24.8 kg of P₂O₅ and 21.6 kg of K₂O per 10 ares was added and the soil irrigated amply. Six nursery plants of cv. Kokei No. 14 were planted on 20 May. The soil in the first box was heated from 18:00 to 6:00 between 23 August and 1 October by an electric heating cables set in the soil (heat plot). The soil in the second box was cooled from 18:00 to 6:00 during the same period by running cool underground water through an inbedded hose (cool plot). Since the optimum soil temperature for the growth of sweet potato plants ranges from 20 °C to 30 °C (Hasegawa and Yahiro, 1957), the highest soil temperature during heating was set up to 30 °C, and the lowest during cooling at 20 °C. The soil in the third box (control) was not manipulated, and the soil was irrigated amply. On 1 October, the plants were dug and the leaves and stems (aerial portions) and roots weighed separately.

The skin colors of the tuberous roots was classified visually into 5 grades from whitish pink (1) to brilliant red (5); those above 4 are considered high quality, remarkable sweet potatoes. Skin plugs were excised with 10 mm diameter cork borer, weighed and extracted with 10 ml of methanol acidified with 0.02% HCl for anthocyanin analysis. The optical densities of the crude extracts were measured with a spectrophotometer at 510 nm. Sugar and starch content was determined as in Exp. 1. Daily maximum and minimum soil temperatures in each plot were recorded from 24 August to 1 October and average temperatures during 5 days were calculated.

Results

Experiment 1. Diurnal changes of sugar content in the stem, and sugar and starch content in the field-grown root

The average fresh weight of plants dug at 5:00, 11:00, 17:00, and 23:00 on 27 September were 7250, 7800, 10,650 and 7666 g, respectively. Sucrose content in the stem was 44.5 mg · g⁻¹ DW and increased gradually, reaching 72.0 mg · g⁻¹ DW at 23:00 (Table 1). Although glucose and fructose in the stem were less than 14 mg · g⁻¹ DW, they had the same tendency as sucrose (Table 1). Sucrose content in the root was around 60 mg · g⁻¹ DW at 5:00 and 11:00, and increased to 70.5 and 82.2 mg · g⁻¹ DW, at 17:00 and 23:00, respectively (Table 1). No glucose or fructose were observed in the root (Table 1). Starch content in the root was 253.2 mg · g⁻¹ DW at 11:00, and attained a maximum at 5:00, 312.8 mg · g⁻¹ DW (Table 1).

Experiment 2. Effects of night soil-temperature on sugar content in the stem, and sugar and starch content in the root

The average maximum soil temperatures in the control, heat and cool plots were: 29.3 °C, 31.1 °C, 29.3 °C, and the average minimum temperatures were 21.8 °C, 27.2 °C, 19.2 °C, respectively (Fig.1). The total fresh weights of the aerial portion for the control, heat and cool plots were: 968, 1015 and 708 g, respectively, while the total root fresh weights per plant, respectively, were: 778, 333 and 745 g (Table 2). The average root

Table 1. Diurnal changes of sucrose, glucose and fructose content in stems and roots, and starch content in roots.

Time in a day ^z	Stem (mg · g ⁻¹ DW)			Root (mg · g ⁻¹ DW)			
	Sucrose	Glucose	Fructose	Sucrose	Glucose	Fructose	Starch
5:00	44.5b ^y	4.6a	2.8a	54.9c	tr	tr	312.8a
11:00	50.4b	2.1a	1.0a	59.9c	tr	tr	253.2b
17:00	53.6b	8.9a	11.1a	70.5b	tr	tr	266.1b
23:00	72.0a	12.7a	13.6a	82.2a	tr	tr	301.8a

^z 5:00; just before sunrise. 11:00; during active photosynthesis. 17:00; at dusk. 23:00; complete darkness.

^y Different letters in the same column denote significant difference, *P* < 0.05, by Duncan's multiple range test.

fresh weights, respectively: 233, 95 and 263 g, and the mean number of tubers per plant were respectively, 3.8, 3.5 and 2.8 (Table 2). The root skin color index was 4.6 or brilliant red in the cool plot, but 3.2 or almost pink in

the heat plot (Table 2). The OD of anthocyanin extract was highest in the control (0.54), but 0.41 in the heat plot (Table 2). Sucrose content in the stem was high, 91.2, 82.5 $\text{mg} \cdot \text{g}^{-1} \text{DW}$, in the control and cool plots, respectively, but low in the heat plot (Table 3). While glucose and fructose in the stem were less than 30 $\text{mg} \cdot \text{g}^{-1} \text{DW}$, their trend was similar to that of sucrose (Table 3). Sucrose content in the root was highest, 103.9 $\text{mg} \cdot \text{g}^{-1} \text{DW}$ in the heat and lowest, 76.4 $\text{mg} \cdot \text{g}^{-1} \text{DW}$, in the cool plot (Table 3). Glucose and fructose were under 5 $\text{mg} \cdot \text{g}^{-1} \text{DW}$, in all plots (Table 3). Starch content was 251.2 $\text{mg} \cdot \text{g}^{-1} \text{DW}$ in the cool plot, whereas it was 192.3 and 199.8 $\text{mg} \cdot \text{g}^{-1} \text{DW}$ in the heat and the control plots, respectively (Table 3).

Discussion

In Exp.1, sucrose content in the stem and root was the lowest at 5:00 and increased to a maximum at 23:00. Sucrose photosynthesized in the leaf of sweet potatoes translocates to the root rapidly via the stem (Murata, 1970). The velocity of sucrose transport in sieve tube of most plants is between 10 and 100 $\text{cm} \cdot \text{hr}^{-1}$ (Kursanov, 1984; Peel, 1975). Rice leaves translocate photosynthates to roots within 24 hours (Moriwaki, 1974). Sunlight from 5:44 to 17:45 was bright on 27th September (Meteorological almanac of Kanazawa in 1999). So that sucrose content in the stem probably begins to increase simultaneously with sunrise, and continues until 11:00 and 17:00. The maximum content at 23:00 is due to the active translocation of the photosynthate to stems from leaves. The accumulation of sucrose by the roots un-

Fig. 1 Seasonal fluctuations in maximum (upper) and minimum (lower) soil temperatures in the control and heat and cool plots during root formation in sweet potatoes.

Table 2. Effect of night soil – temperature on plant growth and root characteristics.

Treatments	Total fresh weight		Average root fresh weight ($\text{g} \cdot \text{root}^{-1}$)	Number of root $\cdot \text{plant}^{-1}$ ^y	Skin color index ^x	OD ^w
	Leaf and stem ($\text{g} \cdot \text{plant}^{-1}$)	Root ($\text{g} \cdot \text{plant}^{-1}$)				
Control	968 a ^z	778 a	233 a	3.8 a	4.2 b	0.54 a
Heating	1015 a	333 b	95 b	3.5 a	3.2 c	0.41 b
Cooling	708 a	745 a	263 a	2.8 a	4.6 a	0.46 a

^z Different letters in the same column denote significant difference, $P < 0.05$, by Duncan's multiple range test.

^y Number of roots weighing above 50 g.

^x The color of the root was classified into 5 visual grades from whitish pink (1) to brilliant red (5).

^w The optical density (OD) of the crude extracts was measured with a spectrophotometer at 510 nm.

Table 3. Effect of night soil – temperature of carbohydrate content in stems and roots.

Treatments	Stem ($\text{mg} \cdot \text{g}^{-1} \text{DW}$)			Root ($\text{mg} \cdot \text{g}^{-1} \text{DW}$)			
	Sucrose	Glucose	Fructose	Sucrose	Glucose	Fructose	Starch
Control	91.2a ^z	11.1a	10.6a	82.2b	4.1a	4.5a	199.8b
Heating	53.7b	0.5b	3.6b	103.9a	3.2a	2.7a	192.3b
Cooling	82.5a	12.9a	28.7a	76.4b	0.1a	0.9a	251.2a

^z Different letters in the same column denote significant difference, $P < 0.05$, by Duncan's multiple range test.

doubtedly parallels to that in the stem because sweet potato roots are located just beneath the main stem.

In Exp. 1, starch content in the root was low at 11:00 and 17:00 but the highest at 5:00. Sucrose translocated into the sweet potato root is normally synthesized into starch but starch biosynthesis is stopped when roots are exposed to sunlight because adenosine diphosphate-glucose (ADPG), a rate limiting factor for starch synthesis is inactivated (Murata, 1971). Therefore, starch formation in the root may be suppressed by sunlight during day, even if the root grows in the soil, but it is rapid at night owing to a large quantity of ADPG that is present, resulting in a rapid deposition of starch between 23:00 and 5:00. That would account for the low sucrose content at 5:00.

The growth of tuberous roots of sweet potatoes (Nisiuti, 1948; Hasegawa and Yahiro, 1957; Kato and Nakayama, 1975) and potato tubers (Yamamoto and Noda, 1952; Sugi and Ando, 1953) is accelerated under lower soil temperature. These findings on sweet potatoes are inconsistent with the results of Exp. 2. Sucrose content in stems was high in the cool but low in the heat plots. The low sucrose content in stems in the heat treatment may be attributed to active transport of sucrose from stem to root brought about by the high respiration rate of the roots. Sucrose content in roots was high in the heat and low in the cool plots, but inverse to starch. Low soil temperature favours starch accumulation (Sugi and Ando, 1953) as well as their specific gravity which is closely related with starch content of potato tubers (Yamamoto and Noda, 1952). Furthermore, starch formation from photosynthates is active in rice plants under low- (Ota and Yamada, 1958; Sato, 1966), but not at high- temperatures (Sato, 1972, 1974). High temperature causes the inflow of assimilates into the rice grains to end early (Sato and Inaba, 1976), while increases the respiration rate (Sato, 1966, 1972). Therefore, in low night soil-temperature starch can be actively formed from the transported sucrose because it favours growth as there is a smaller demand for respiratory substrates.

The values of skin color of the root and optical density were high in the cool, but low in the heat plots. While high sucrose and starch contents are essential, color index above 4 is recommended for high quality, marketable sweet potatoes. The conspicuous root color, that is due to anthocyanins (Yamaguchi, 1978), is closely correlated with its sugars and starch contents (Kato and Nakayama, 1975), whereas mealiness is related to high starch content in the root (Sakamoto, 1989). In corn endosperm tissue cultures (Straus, 1959) and in detached petals of *Impatiens balsamina* L. (Klein and Hagen, 1961), sucrose promotes anthocyanin production. From these results, high sucrose and starch content in the low night soil-temperature is considered to produce brilliant red color and mealy roots.

Therefore, we conclude that sucrose transported into

the root is actively synthesized into starch mainly during the night so that low night soil-temperature favours the production of high quality, marketable sweet potatoes.

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サツマイモ (*Ipomoea batatas* Poir.) のスクロースとデンプン含量の日変化 ならびにこれらの含量に及ぼす生育後期の夜間地温の影響

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摘 要

サツマイモ (*Ipomoea batatas* Poir.) を圃場と夜間の地温を低温、高温および適温に制御した箱で栽培した。圃場のものは、9月27日の5時、11時、17時および23時に掘り上げた。各時刻の植物体の総新鮮重は、7250 g、7800 g、10650 g、7666 gであった。茎中のスクロース含量は5時には $44.5 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ で、その後、漸増し23時には $72.0 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と最大となった。塊根中でも5時に $54.9 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と最も小さく、その後、増加し23時には $82.2 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と最大となった。塊根中のデンプン含量は、5時に $312.8 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と最大で、11時に $253.2 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と最小となった。これらの結果から、塊根では夜間にスクロースよりデンプンが活発に合成されるものと考え

られた。夜間の地温が茎および塊根中の糖およびデンプン含量に及ぼす影響を調査した結果、茎中のスクロース含量は対照区、低温区で大きく、高温区で小さくなった。塊根中のスクロース含量は、高温区で $103.9 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と大きく低温区で $76.4 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と小さかったのに対し、デンプン含量は低温区で $251.2 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と大きく、高温区で $192.3 \text{ mg} \cdot \text{g}^{-1} \text{ DW}$ と小さくなった。また、塊根の皮色は低温区で最も鮮やかになった。これらの結果から、夜間の地温を低温に保持することによりスクロースよりデンプンが活発に合成される結果、塊根中のデンプン含量は高くなり、皮色が鮮やかで粉質の高品質の塊根が形成されるものと考えられた。