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Summary

Most of heating energy has relied on the fuel in horticulture, and Japanese horticulture mainly has been dependent on oil. Recently, both of the high yield performance and energy-saving temperature management have been a key for fruit grown in a plastic house with heating. To establish the energy-saving night temperature regime in Satsuma mandarin (*Citrus unshiu* Marc.), I mainly analyzed the response of fruit growth to environment.

1. I discussed how temperature and other environmental factors affect the fruit growth and quality of Satsuma mandarin grown in a plastic house with heating. At 14–23°C, the average nighttime air temperature was positively correlated with the standardized fruit growth rate (GRF_{St}) in the young stage (60–90 days after full bloom (DAFB)). In contrast, GRF_{St} was clearly depressed with a daytime air temperature at around 30°C, and the optimum air temperature for active fruit growth was 25°C. Moreover, in the middle (90–120 DAFB) and mature (120–180 DAFB) stages, the air temperature did not correlate with the GRF_{St}. These results indicate that, in the young stage, the air temperature should be controlled at around 25°C during the daytime and 20–23°C during the nighttime for active fruit growth. In the middle and mature stages, fruit growth might not require nighttime air temperatures that are as high as 20–23°C. The air temperatures did not correlate with the fruit soluble sugar content (SSC); in contrast, a close relationship was found between the pre-dawn xylem water potential (Ψ_{Xy}) and SSC. The day temperature, radiation and Ψ_{Xy} were linearly correlated with the fruit titratable acidity (TA) in the young stage.

2. In order to improve temperature and water management in the greenhouse cultivation of Satsuma mandarins, short-term water and carbon balance in intact Satsuma mandarin fruits was studied by measuring fruit expansive growth, CO_2 and H_2O gas exchange, sap flux into the fruit through the phloem and xylem, and ^{13}C partitioning. Seventy-one days after full bloom, with day/night temperature set at 28°C/23°C and under fine weather conditions, sap flux through the xylem into the fruit showed a dynamic diurnal change which was related to changes of fruit volume. In leaves, ^{13}C partitioning decreased from 11:00 until 23:00, remaining constant thereafter, whereas in fruits, ^{13}C partitioning increased from 11:00 until 23:00, and then remained contrast. Investigating the cumulative water balance, 19% of water output was lost by fruit transpiration, whereas 81% contributed to fruit growth. In cumulative carbon balance, 39% of carbon output was lost by fruit respiration, whereas 61% contributed to fruit growth. Quantitative analyses of physiological responses to environmental conditions, as measured in this study, are essential for establishing energy-saving temperature management strategies.

3. Light condition is a fundamental environmental factor for high-quality plant production, so I discuss how light condition affects fruit development in the long and short term, and attempt to clarify management methods for active fruit development under conditions of low solar radiation, by using quantitative research on fruit water and carbon balance during greenhouse cultivation of Satsuma mandarin. A significant decrease in yield due to shading was not detected, but we confirmed that shading treatment affected the dry weights of source-sink units, fruit volume, increase in volume of the fruits, and fruit quality parameters, such as sugar accumulation, acid content, and rind color. Qualitatively, the carbon balance of Satsuma mandarin fruit is comparable to that of tomato fruit or rice panicle, but quantitatively, the carbon balance of Satsuma mandarin fruit may differ, as shown by low sink relative growth rate. In addition, fruit growth parameters such as translocation rate for a fruit and fruit relative growth rate showed significant positive correlations with dark respiration, despite the shading treatment. The fruit carbon demand may be simply described by fruit dark respiration as the sum of new photosynthetic carbon and stored carbon translocation for a fruit.

4. In order to clarify the effect of nighttime temperatures on fruit development of Satsuma mandarin, I examined the

fruit water and carbon balances using the ^{13}C tracer method and the roles of phloem and xylem transports for fruit growth under moderate night temperatures (MN, set at 23°C) and low night temperatures (LN, set at 13°C). The average predawn xylem water potentials were -0.79±0.04 MPa under MN and -0.77±0.03 MPa under LN. Fruit growth used 86% of pedicel sap flux toward the fruit, while transpiratory water losses from the fruit surface were 14% of pedicel sap flux under both MN and LN. The daytime integrated xylem sap flux was negative, but it was positive in the nighttime. The integrated phloem sap flux (ΣJ_{Phlo}) and the difference in ΣJ_{Phlo} between MN and LN were only 6–10% and 4% of the total sap accumulated in the fruit, respectively. Integrated fruit photosynthesis and integrated CO_2 efflux from the fruit surface were 7–8% and 22–23% of the total carbon supply toward the fruit, respectively. This indicates that carbon translocation from leaves to fruit via the phloem of the stem is the main source of carbon for the fruit.

5. To meet the needs of producing high quality Satsuma mandarin grown in a heating greenhouse with low fuel consumption, I tried to describe the seasonal nighttime water and carbon translocation from tree to fruit, and to clarify the relationship between fruit growth and yield performance. For high fruit yield in conventional crop load (18 leaf to fruit ratio), at 60–90DAFB, Satsuma mandarin requires moderate nighttime temperature as 23°C for active fruit growth determined by daytime phloem sap inflow and nighttime xylem sap inflow, and for cell division for juice sack cells. At 90–120DAFB, fruit growth might be mainly determined by the phloem sap flow which accelerated by xylem back-flow, however, photosynthetic carbohydrate partitioning was saturated by crop load, and high night temperature does not always increase carbon allocation to fruits even if phloem sap inflow may be increased. If Satsuma mandarin would be low crop load (30 leaf to fruit ratio) condition caused by unsufficient flowering or unfortunate fruit drop, high resource availability suggested to compensate for low night temperature as 17°C if only appreciate water status and daytime temperature were managed.

6. In order to control nighttime temperatures with energy saving, how different night temperature regimes affected on the fruit growth, quality and ^{13}C allocation from leaf to fruit were researched by both the partial heating and whole tree heating. One type, altering time of nighttime heating, the end of day (EOD) -heating, middle of night (MON) -heating, and predawn (Pd) -heating were applied. The EOD-heating temporally activated the fruit growth and accelerated the ^{13}C allocation from leaf to fruit through short term (hours) researches by the partial heating, however, comparing to the conventional heating as 20°C constant in nighttime by the whole tree heating during 60–90 DAFB, no superiority was observed in both the fruit volume increase and fruit quality, and the MON-heating showed the depression of fruit growth. Another type of a regime determined by daily integrated solar radiation, comparing to the conventional heating as 17°C constant in nighttime during 78–120 DAFB, no superiority was observed in the fruit quality. Nighttime ^{13}C allocation from the leaf to fruit was detected at 90 DAFB, though was hardly detected at all at 120 DAFB regardless of night temperatures as high as 25°C at both days.

In conclusion, the nighttime temperature regimes both altering time of that and which determined by solar radiation were not superior to the conventional night temperature regime. A possible energy-saving temperature regime for Satsuma mandarins grown in a plastic house with heating has been developed. Firstly, at 60–90 DAFB, it is necessary to keep the daytime temperature 25°C and not to be lower than 20°C at night. Secondly, at 90–120 DAFB, 17°C might be a sufficiently high nighttime temperature for high quality fruit production. This progressive temperature regime would show apparent energy-saving effects compared to the conventional nighttime regime of 23–25°C from 50–120 DAFB.

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連 絡 先　TEL　0974-28-2074　　FAX　0974-28-2052
　　　　　e-mail：al5082@pref.oita.lg.jp
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