Effects of elevated temperatures during the flowering to physiological fruit drop stage and at the fruit maturation stage on fruit quality of the satsuma mandarin

Keiko Sato\textsuperscript{a+b} and Yoshinori Ikoma\textsuperscript{a+b}

\textsuperscript{a}Citrus Research Station, Institute of Fruit Tree and Tea Science, NARO, 485–6 Okitsu-nakacho, Shimizu, Shizuoka 424–0292, Japan
\textsuperscript{b}Present address: NARO Headquarters, 3–1–1 Kannondai, Tsukuba 305–8517, Japan

Abstract

In recent years, peel puffing and delayed peel pigmentation have been observed in satsuma mandarins, possibly due to global warming. The effects of elevated temperatures during fruit maturation on fruit quality have been well studied. However, little is known about the effects of elevated temperatures during the flowering to physiological fruit drop stage. To clarify this, we controlled the air temperatures around satsuma mandarin trees during the flowering to physiological fruit drop stage (Period A) and at the fruit maturation stage (Period B). Temperatures were set to 2°C or 4°C above the recent mean temperatures because global warming is predicted to increase the mean global surface temperature by 2°C–4°C in this century. We then investigated the effects of the elevated temperatures on fruit quality in varying combinations for Periods A and B. Peel puffing was increased when temperatures were increased by 4°C during Period A or by 2°C or 4°C during Period B. Peel puffing was also increased with increases of 2°C during Period A; however, those results were not statistically significant. Peel pigmentation was enhanced when temperatures were increased by 2°C or 4°C during Period A but deteriorated when the temperature was increased by 2°C during Period B. Fruit weights were increased when temperatures were increased during Period A, but this was partly due to higher peel percentages. The peel percentages tended to be higher after temperature increases in either Period A or Period B. The soluble solid concentrations and acidity levels of the fruit juices tended to be lower after temperature increases during Period A, although not all of those changes were statistically significant. In conclusion, we found that temperature increases of 2°C or more above the recent mean temperatures during early fruit development can be detrimental to fruit quality by increasing peel puffing.

Key words: Global warming, Peel pigmentation, Peel puffing, Phytotron

1. Introduction

Generally, it is thought that global warming could significantly affect crop production in both positive and negative ways (Adams et al., 1998; Moretti et al., 2010; Sugiyama et al., 2012). Using the representative concentration pathway for greenhouse gases of 4.5, or by 4.4°C using RCP8.5, the Ministry of the Environment and the Japan Meteorological Agency (2015) estimated that by the end of this century, temperatures in Japan would increase by 2.0°C, relative to the mean temperatures for 1984–2004. In Japan, increased peel puffing and reduced peel pigmentation have already become problems in satsuma mandarin production due to the recent global warming (Sugiyama et al., 2007). Peel puffing is a physiological disorder where the fruit rind tissues are separated from the flesh (Fig. 1). Puffy mandarins are easily damaged during picking, transporting, sorting, and packing, and their commercial value is dramatically reduced compared with normal fruit. These fruits are susceptible to earlier postharvest decay and taste deterioration when compared with normal fruits, and therefore, puffy mandarins cannot be stored for long periods.

Climate conditions at the fruit maturation stage affect peel puffing; the incidence of peel puffing increases with elevated relative humidity and/or elevated temperature (Kawase, 1984; Yokoo et al., 1963). There have also been many studies on the effects of air temperature during the maturation stage on the levels of peel pigmentation (Kurihara, 1968; Nii et al., 1970; Reuther, 1973; Utsunomiya et al., 1982). Both the decomposition of chlorophyll and the biosynthesis of carotenoids in the peel are suppressed at 30°C or higher during this stage (Nii et al., 1970; Utsunomiya et al., 1982). By contrast, there have been few studies on the effects of temperature during the flowering to physiological fruit drop stage on fruit quality, including peel puffing and peel pigmentation.

It is possible that satsuma mandarin cultivation areas will gradually move northward and inland due to global warming (Sugiyama et al., 2016). However, given the time it takes for fruit trees, including satsuma mandarin trees, to grow and reach their productive phase, it is not easy for farmers to move to new cultivation sites. It is desirable for farmers to continue satsuma mandarin cultivation in the current orchards, using adaptive cultivation techniques and countermeasures to cope with the negative impacts of global warming. Therefore, it is important to clarify the influences of elevated temperatures on the fruit quality of satsuma mandarins.

The goal of this study was to clarify the effects of higher
temperatures on the aspects of fruit quality, including peel puffing and peel pigmentation, during two fruit development periods: from flowering to the physiological fruit drop stage (Period A) and at the fruit maturation stage (Period B).

2. Materials and Methods

The study was conducted during 2013–2015 at the NARO Institute of Fruit Tree and Tea Science, Citrus Research Station, Okitsu, Shimizu, Shizuoka, Japan (35.05°N, 138.52°E). The climate normal for temperature during the 30 years between 1981 and 2010 in our experimental field was 16.3°C. The satsuma mandarin (Citrus unshiu Marcow., cv Nankan 20 gou) trees had been grafted onto the rootstocks of trifoliate orange (Poncirus trifoliata (L.) Raf.) trees. The grafted trees were planted in 25 L polypropylene pots and grown in the field. We used 3-year-old trees in 2013 and 2014 and 5-year-old trees in 2015. The temperature treatments were conducted during the flowering to physiological fruit drop stage (Period A) and the maturation stage (Period B) using two phytotrons (TPE-6S, ESPEC MIC Corp.). Since there have been few studies of the effects on fruit quality of temperatures during the flowering to physiological fruit drop stage (Period A), we laid out an experimental design with temperature rises during spring and early summer in this study. The dates set for each period in each year are presented in Table 1. One of the phytotrons was set at the recent mean temperatures for Okitsu (±0°C), based on the 1981–2010 climate normal for temperature obtained with the automated meteorological data acquisition system at Shimizu, located in our experimental field. The 10-day means of daily maximum, minimum, and average temperatures during Periods A and B obtained from the climate normal data are presented in Table 2. The other phytotron was set to +2°C (2013) and +4°C (2014 and 2015) relative to the temperatures in the ±0°C phytotron. The temperatures were set to vary depending on the time of day, with minimum temperatures from 0:00 to 4:00 h, maximum temperatures from 12:00 to 16:00 h, and daily

![Fig. 1. Puffing fruit. Left: Puffing fruit; right: normal fruit](image)

| Year | Treatment period | The dates set for each period | Days | Average humidity ± 0°C | +2 or 4°C |
|------|------------------|-----------------------------|------|------------------------|----------|
| 2013 | Period A         | Apr. 30 (beginning of bloom stage) – Jun. 4 (physiological fruit drop stage) | 36   | 69.2% | 70.7% |
|      |                   | Oct. 28 (beginning of peel coloring stage) – Dec. 20 | 54   | 73.7% | 76.1% |
| 2014 | Period A         | May 12 (full bloom stage) – Jun. 9 (physiological fruit drop stage) | 29   | 71.2% | 67.0% |
|      |                   | Oct. 31 (half of fruit were coloring) – Dec. 2 | 33   | 78.7% | – |
| 2015 | Period A         | May 7 (full bloom stage) – Jun. 9 (physiological fruit drop stage) | 34   | 72.3% | N.D.* |
|      |                   | Oct. 30 (70% of fruit were coloring) – Dec. 1 | 33   | 77.6% | 77.4% |

*Data were not obtained
average temperatures from 6:00 to 10:00 h and from 18:00 to 22:00 h, as presented in Fig. 2. The temperatures also varied according to the time of year (i.e., late April to mid-December), as presented in Table 2. Air temperature and humidity were measured using data loggers (RTR-53A, T&D Corporation, Nagano, Japan) with their sensors covered by radiation shields (41304PY, Field Pro, Inc., Tokyo, Japan). The temperatures on Nov. 17, 2013, and Nov. 19, 2015, are presented in Fig. 3. The average humidity during the treatments in each year is presented in Table 1. During the treatment period, appropriate watering was performed to prevent water stress on the trees. The trees were kept in the field between Periods A and B. Trees with leaf/fruit ratios greater than 20 were thinned out to 20 in July, and trees with leaf/fruit ratios of 20 or less were not thinned out.

Fruit measurements were conducted on the day the fruits subjected to the $\pm 0^\circ$C treatment were almost fully colored.

Table 2. Daily average, mean daily minimum, and mean daily maximum temperatures ($^\circ$C) during satsuma mandarin fruit development periods in Okitsu, Japan.

| Period | Daily average | Mean minimum | Mean maximum |
|--------|---------------|---------------|--------------|
| A      |               |               |              |
| late Apr | 16.2          | 11.9          | 21.1         |
| early May | 17.6          | 13.5          | 22.3         |
| mid-May | 18.4          | 14.5          | 22.9         |
| late May | 19.5          | 15.5          | 24.0         |
| early Jun | 20.8          | 17.2          | 25.1         |
| B      |               |               |              |
| late Oct | 16.9          | 13.2          | 21.5         |
| early Nov | 15.5          | 11.6          | 20.1         |
| mid-Nov | 13.6          | 9.8           | 18.2         |
| late Nov | 12            | 8.1           | 16.8         |
| early Dec | 10.2          | 6.1           | 15.2         |
| mid-Dec | 8.8           | 4.6           | 13.8         |

For each treatment, fruit quality analyses were conducted using 25 fruits (5 from each of five potted trees) in 2013, 9 fruits (3 from each of three trees) in 2014, and 15 fruits (5 from each of three trees) in 2015. Different sets of trees were used each year. Fruit weight, peel percentage, peel pigmentation, and peel puffing were assessed. Measurements of the soluble solid concentration (SSC) and acidity were conducted using the juices of five fruits from each of five potted trees (five biological replications) in 2013, three fruits from each of three trees (three biological replications) in 2014, and five fruits from each of three trees (three biological replications) in 2015. Fruits were randomly collected for these assessments. Measurements were conducted on Dec. 20 in 2013, Nov. 24 and Dec. 2 in 2014, and Dec. 1 in 2015. The level of peel puffing was assessed by finger touch and rated as 0, 1, 2, or 3, indicating a range from firm (0) to marked puffing (3) (Kawase and Suzuki, 1981; Kawase, 1987; Fig. 4). Peel pigmentation was measured using a colorimeter (NF-333, Nippon Denshoku Industries Co., Ltd. Tokyo, Japan), and a*/b* values were calculated. This ratio increases as the color progresses from yellow through orange to red. We used a*/b* values from the CIELAB scale because they are highly correlated with a/b values from the Hunter L, a, b scale (Sato et al., 2015). The a/b values are highly correlated with the observed color of the fruits (Stewart and Wheaton, 1971). The peel percentage was defined by dividing peel weight by fruit weight and is closely correlated with peel puffing (Inoue, 1980). The SSC and acidity of the juice samples were measured using an NH-2000 meter (HORIBA, Japan).

Data were subjected to a two-way analysis of variance, and the means were separated using Tukey’s test or t-test at $P < 0.05$ using JMP13 (SAS Institute, Inc., NC, USA). The percentage data were transformed using arcsine before statistical analysis.

3. Results and Discussion

The results from 2013 are presented in Table 3. When trees were kept at $+2^\circ$C during Period A, the fruit weight was increased. The peel percentages for fruits kept at $+2^\circ$C during Period A or Period B were increased. Peel puffing was
accelerated in fruits kept at +2°C during Period B. The peel pigmentation levels were enhanced in fruits kept at +2°C during Period A and deteriorated in fruits kept at +2°C during Period B. The SSC in fruits kept at +2°C during Period A was decreased. No significant differences in acidity were observed among the treatments. Thus, when temperatures were elevated by 2°C above normal during Period A, the fruit weight, peel percentage, peel pigmentation, and SSC were affected. Temperatures elevated by 2°C during Period B also affected peel percentage, peel puffing, and peel pigmentation.

Although the elevated temperature during Period A tended to increase peel puffing, the results were not statistically significant (Table 3), perhaps due to the slight temperature difference (+2°C). Therefore, we investigated the effects on fruit quality of 4°C above the recent mean temperatures. In 2014, we compared treatments of ±0°C and +4°C during Period A, with all trees at ±0°C during Period B. Considering the possibility of advancing the harvest of the fruits treated with +4°C during

Table 3. Effect of high temperature on fruit quality in 2013.

| Treatment       | Fruit weight (g) | Peel percentage (%) | Peel puffing (0–3) | Peel pigmentation (a*/b*) | SSC (Brix) | Acidity (%) |
|-----------------|------------------|---------------------|--------------------|--------------------------|------------|-------------|
| Period A        | Period B         |                     |                    |                          |            |             |
| ± 0°C           | ± 0°C            | 129.5               | 19.7               | 0.0                      | 0.46       | 10.0        | 0.64        |
| ± 0°C           | + 2°C            | 147.3               | 20.9               | 1.0                      | 0.42       | 9.9         | 0.61        |
| + 2°C           | ± 0°C            | 159.6               | 20.4               | 0.2                      | 0.47       | 9.4         | 0.58        |
| + 2°C           | + 2°C            | 158.3               | 23.1               | 0.8                      | 0.45       | 9.5         | 0.60        |

ANOVA

| Temp. of period A | *         | *         | NS         | *         | *         | NS         | NS         |
|-------------------|-----------|-----------|------------|-----------|-----------|------------|------------|
| Temp. of period B | NS        | *         | *          | *         | NS        | NS         | NS         |
| A × B             | NS        | NS        | NS         | NS        | NS        | NS         | NS         |

NS and * indicate not significant and significant differences of $P < 0.05$ respectively, by ANOVA ($n=25$ for fruit weight, peel percentage, peel pigmentation, and peel puffing; $n=5$ for SSC and acidity).
Period A, we conducted fruit measurements both 1 week before harvesting and at the time of harvesting. Fruit weights were significantly higher in fruits treated with +4°C during Period A and measured 1 week before harvesting than in those treated with ±0°C. The fruits measured at harvesting also had higher weights after treatment with +4°C, but the difference was not statistically significant (Table 4). The peel percentages and peel puffing were also increased in fruits treated with +4°C during Period A, both when measured at harvesting and 1 week before. Peel pigmentation was promoted by the +4°C treatment, with significant differences in the fruits measured at harvesting. No significant differences were observed in the SSC, but the acidity was decreased in fruits treated with +4°C during Period A. Peel puffing in fruits treated with +4°C was significantly increased at 1 week before harvesting and during harvesting. The results in 2014 demonstrated that the +4°C elevated temperature during Period A significantly affected peel percentage, peel puffing, and acidity. Fruit weight and peel pigmentation also tended to be influenced by the higher temperature.

In 2015, we investigated the effects on fruit quality of elevated temperatures (+4°C) during both Periods A and B. We laid out an experimental design with treatments of ±0°C or +4°C during Period A and ±0°C or +4°C during Period B. As in 2014, fruit weight was increased in fruits treated with +4°C during Period A (Table 5). There was interaction between Periods A and B for the peel percentage, with the highest percentages in fruits treated with +4°C during Period A and ±0°C during Period B. Peel puffing increased in fruits treated with +4°C during Period A and/or Period B. Peel pigmentation was enhanced in fruits treated with +4°C during Period A. No significant differences in SSC or acidity were observed among the treatments. The results in 2015 demonstrated that the temperature increase (4°C) during Period A affected the fruit weight, peel puffing, and peel pigmentation. The temperature increase of 4°C during Period B also accelerated peel puffing.

Collectively, the results in 2014 and 2015 revealed that the fruit weight, peel puffing, and peel pigmentation were increased by treatment with +4°C during Period A. The peel percentage also tended to be higher in fruits treated with the higher temperature. Peel puffing was also enhanced by the higher temperature during

Table 4. Effect of high temperature on fruit quality in 2014.

| Treatment | Period A | Period B | Fruit weight (g) | Peel percentage (%) | Peel puffing (0–3) | Peel pigmentation (a*/b*) | SSC (°Brix) | Acidity (%) |
|-----------|----------|----------|------------------|--------------------|-------------------|--------------------------|------------|------------|
| ± 0°C     | ± 0°C    |          | 116.6            | 22.7               | 0.1               | 0.40                     | 11.5       | 0.84       |
| + 4°C     | ± 0°C    |          | 139.1            | 26.6               | 2.2               | 0.40                     | 10.9       | 0.67       |

Table 5. Effect of high temperature on fruit quality in 2015.

| Treatment | Period A | Period B | Fruit weight (g) | Peel percentage (%) | Peel puffing (0–3) | Peel pigmentation (a*/b*) | SSC (°Brix) | Acidity (%) |
|-----------|----------|----------|------------------|--------------------|-------------------|--------------------------|------------|------------|
| ± 0°C     | ± 0°C    |          | 82.9             | 22.4 b             | 0.5               | 0.43                     | 14.3       | 1.17       |
| ± 4°C     | ± 0°C    |          | 89.4             | 23.7 ab            | 1.5               | 0.44                     | 13.6       | 0.99       |
| + 4°C     | ± 0°C    |          | 117.1            | 24.6 a             | 1.4               | 0.49                     | 14.2       | 0.91       |
| + 4°C     | + 4°C    |          | 122.5            | 23.7 ab            | 2.5               | 0.48                     | 13.9       | 0.85       |

ANOVA

| Temp. of period A | * | NS | * | * | NS | NS |
| Temp. of period B | NS | NS | * | NS | NS | NS |
| A × B             | NS | *  | NS | NS | NS | NS |

NS and * indicate not significant and significant differences, respectively, at P < 0.05 using Tukey’s test (n=9 for fruit weight, peel percentage, peel pigmentation, and peel puffing; n=3 for SSC and acidity).
Period B.

It is clear that peel puffing is promoted when fruits at the maturation stage are subjected to high temperatures and high humidity or heavy rain (Kawase, 1984; Yokoo et al., 1963). In this study, peel puffing was increased by treatment with +2°C or +4°C above the recent mean temperatures during Period B (Tables 3, 5). Peel puffing was also increased by treatment with +4°C during Period A (Tables 4, 5). Kawase (1984) reported that peel puffing was increased in fruits treated with temperatures set at 5°C above the mean and humidity maintained at almost 75% during the maturation stage, when compared with fruits kept at the mean temperature. The mean temperatures used by Kawase (1984) were almost the same as the temperatures set at ±0°C in our study. Therefore, our results were consistent with those of Kawase (1984), and we further showed that the temperature increase of only +2°C can also increase peel puffing.

High temperatures during the young fruit (cell division) stage promoted fruit enlargement in Japanese pear and peach (Hayama et al., 2007; Sugiuira et al., 1995). Inoue and Chien (1987) reported that in satsuma mandarin, a relatively high temperature of 25°C during around 1 month after full bloom caused the growth of larger fruits than those grown at 15°C during the same period. In this study, fruit weight was increased in fruits treated with +2°C or +4°C during Period A (Tables 3–5). In 2013, the average temperature at +2°C during Period A was 20.5°C; in 2014, the average temperature at +4°C during Period A was 23.6°C; and in 2015, the average temperature at +4°C during Period A was 23.1°C. Therefore, our results for the temperature and fruit weight are in line with those of Inoue and Chien (1987), and we further showed that only small temperature increases (+2°C or +4°C) could cause increases in fruit weight. Peel percentages were also increased in fruit treated with +2°C or +4°C during Period A (Tables 3–5). The increases in fruit weight seemed to be attributable to the increases in peel weight. In satsuma mandarin, peel thickness peaks near the end of June and beginning of July, when the fruits begin to grow rapidly (Kuraoka and Kikuchi, 1961). The juice sacs begin to grow rapidly in late June, after the peel has grown. Thus, high temperatures during Period A seemed to enhance peel growth because that is the period when peel growth occurs. Large fruits with high peel percentages tended to have higher degrees of peel puffing (Kawase, 1984). Therefore, the treatment of +4°C during Period A in our 2014 and 2015 experiments promoted fruit and peel growth, and it appears that this led to increases in peel puffing. Because there have been few reports on the effects of temperature increase during the flowering to physiological fruit drop stage on peel puffing, our results are valuable information. The reasons for the correlation between Periods A and B in peel percentages are unknown.

Peel pigmentation was enhanced in fruit treated with +2°C or +4°C during Period A (Tables 3–5). In Japanese pear and peach, high temperatures during the young fruit stage shorten the time needed for fruit development and led to earlier harvest times (Hayama et al., 2007; Sugiuira et al., 1995). The enhanced peel pigmentation in this study may indicate a similar effect in satsuma mandarin, with high temperatures during the young fruit stage shortening the time needed for early fruit development. It is possible that the optimal harvest time for fruits treated with higher temperatures during Period A was earlier than the actual day of harvest, which was the optimal harvest time for the fruits treated with ±0°C during Period A.

In 2013, we found that pigmentation levels were reduced in fruits subjected to the +2°C treatment during Period B (fruit maturation). Studies by Nii et al. (1970), with 1 month of preharvest treatment and constant day/night temperatures, showed that carotenoid levels in the peels of satsuma mandarins at harvest were the greatest after treatment with 20°C, slightly lower with 15°C, and appreciably lower with treatments of 25°C or 30°C. Utsumi et al. (1982) reported that the chlorophyll degraded and the carotenoids accumulated to greater extents with treatment at 15°C than with treatment at 23°C, when the fruits were treated for almost 6 weeks preharvest with constant day/night temperatures. They found that chlorophyll degradation and carotenoid accumulation were inhibited at 30°C. Kawase (1984) reported that peel pigmentation was delayed in fruits treated with temperatures set at +5°C above the mean, when compared with fruits treated with mean temperatures. In our study, the +2°C temperatures in late October, when the Period B treatment began, had a mean of 18.9°C, a maximum of 23.5°C, and a minimum of 15.2°C. The inferior peel pigmentation may have been caused by the maximum temperature being higher than the optimal range of 15°C–20°C for peel coloring. On the other hand, in 2015, the temperature during Period B had no significant effect on the pigmentation levels, even though the maximum temperature at the beginning of Period B for the +4°C treatment was 25.5°C. This difference between 2013 and 2015 might be explained by differences in the fruit coloration stage at the beginning of Period B. In 2013, Period B was started at the beginning of the peel coloring stage in fruits subjected to the ±0°C treatments, whereas in 2015, Period B was started when 70% of the fruits were coloring. It may be that the differences in the peel coloring level at the start of the treatment affected the results. We surmised that the suppression of coloring by high temperature was unlikely to occur if the peel coloring was advanced in more than half of the fruit.

We found that elevated temperatures during Period A tended to decrease the SSC and acidity levels, although not all of these results were statistically significant (Tables 3–5). As discussed above, high temperatures during the early fruit development stages accelerated fruit development and led to earlier harvest times in Japanese pear and peach (Hayama et al., 2007; Sugiuira et al., 1995). It is likely that this also occurred in the satsuma mandarins in this study, with the fruits treated with higher temperatures developing more rapidly than the control fruits, leading to lower SSC and acidity levels at harvest. Our results may be statistically significant with higher numbers of biological replications.

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References

Adams RM, Hurd BH, Lenhart S, Leary N, 1998: Effects of global climate change on agriculture: an interpretative review. *Climate research* **11**, 19–30.

Hayama H, Fujimaru O, Iwatani A, Ito A, Sakamoto D, Okada S, Kashimura Y, 2007: Influence of temperature during fruit growing season on fruit development of ‘Akatsuki’ peach. *Horticultural Research (Japan)* **6**, 201–207.

Inoue H, 1980: Bulk density in relation to the fruit development of satsuma mandarin. *Technical Bulletin of Faculty of Agriculture–Kagawa University* **31**, 105–111.

Kawase K, 1984: Studies on the factors causing satsuma mandarin rind puffing and its control. Ph.D. Thesis. Kyoto University.

Kawase K, 1987: Fruit survey method. *Citrus survey method*. Shizuoka. pp. 5–12.

Kawase K, Suzuki K, 1981: Use of growth regulators to control rind puffing of satsuma mandarin fruit. *Proceedings of the International Society of Citriculture*. 9–12 November, 1981. Tokyo, Japan. pp. 237–239.

Kuraoka T, Kikuchi T, 1961: Morphological studies on the development of citrus fruits. I. Satsuma orange. *Journal of the Japanese Society for Horticultural Science* **30**, 189–196.

Kurihara A, 1968: Fruit growth of satsuma orange under controlled condition. I. Effects of preharvest temperature of fruit growth, color development and fruit quality in satsuma orange. *Bulletin of the Horticultural Research Station* **A8**, 29–37.

Ministry of the Environment, Japan Meteorological Agency, 2015: *The climate of Japan at the end of the 21st century*. Available online: http://www.env.go.jp/earth/ondanka/pamph_tekiou/2015/jpnclim_full.pdf

Moretti CL, Mattos LM, Calbo AG, Sargent SA, 2010: Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: a review. *Food Research International* **43**, 1824–1832.

Nii N, Harada K, Kadowaki K, 1970: Effect of temperature on the fruit growth and quality of satsuma oranges. *Journal of the Japanese Society for Horticultural Science* **39**, 309–317.

Reuther W, 1973: Climate and citrus behavior. In: *The citrus industry. Vol. III*. University of California, USA, pp. 280–337.

Sato K, Ikoma Y, Matsumoto H, Nakajima N, 2015: Effect of spray concentrations and spray times of gibberellin and prohydrojasmon on peel puffing and peel color in satsuma mandarin fruit. *Horticultural Research (Japan)* **14**, 419–426.

Stewart I, Wheaton TA, 1971: Effect of ethylene and temperature on carotenoid pigmentation of citrus peel. *Florida State Horticultural Society* **84**, 264–266.

Sugiura T, Horjo H, Sugaya H, 1995: Relationship between air temperature and fruit growth of Japanese pear (*Pyrus pyrifolia* Nakai). *Journal of Agricultural Meteorology* **51**, 239–244.

Sugiura T, Kuroda H, Sugiura H, 2007: Influence of the current state of global warming on fruit tree growth in Japan. *Horticultural Research (Japan)* **6**, 257–263.

Sugiura T, Sakamoto D, Koshita Y, Sugiura H, Asakura T, 2016: Changes in locations suitable for satsuma mandarin and tankan cultivation due to global warming in Japan. *Proceedings of the International Symposia on the Physiology of Perennial Fruit Crops and Production Systems and Mechanisation, Precision Horticulture and Robotics*, ed. by Tustin DS, van Hooijdonk BM. December 9, 2016. Brisbane, Australia. pp. 91–94.

Sugiura T, Sumida H, Yokoyama S, Ono H, 2012: Overview of recent effects of global warming on agricultural production in Japan. *JARQ* **46**, 7–13.

Utsumi N, Yamada H, Kataoka I, Tomana T, 1982: The effect of fruit temperatures on the maturation of satsuma mandarin (*Citrus unshiu* Marc.) fruits. *Journal of the Japanese Society for Horticultural Science* **51**, 135–141.

Yokoo M, Okudai N, Kozono T, Iwasa S, Osaki M, 1963: Studies on the puffing of peel in satsuma oranges. *Bulletin of the Fruit Tree Research Station* **D1**, 29–44.