Assessment of deterioration in skin color of table grape berries due to climate change and effects of two adaptation measures

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Abstract

We evaluated changes in skin color of table grapes induced by climate change and the effects of a phenological shift caused by cultivation under cover and the use of a superior-color cultivar as adaptation measures. To assess the phenological shift, a model to estimate full-flowering date from air temperature was developed from observed full-flowering date in Japan. A projected air temperature dataset until 2100 with 1-km resolution was applied to this model and the model to estimate skin color developed in the previous report. The full-flowering date of ‘Kyoho’ in open field gradually advanced and was about 9 days earlier in 2031–2050 and 10–25 days earlier in 2081–2100 than in 1981–2000. The skin color rating of ‘Kyoho’ in open field decreased from 9.4 in 1981–2000 to 7.9 in 2031–2050 and to 7.0 in 2081–2100 under the representative concentration pathway 4.5 scenario. The difference in skin color under different emission scenarios increased from around 2040 until the end of this century. Geographical distribution of the frequency of occurrence of poor skin color (skin color rating <7.5) showed that it will be necessary to introduce some adaptation measures for ‘Kyoho’ in open field in the plains of most areas except northern Japan by the middle of this century. Because air temperature during the coloring period drops with advancing phenology, a larger phenological shift led to darker skin. The skin color rating of ‘Kyoho’ at the end of this century remained above 7.5 owing to a phenological shift in plastic greenhouses with side film even in southern Japan. That of ‘Suzuka’, a superior-color cultivar, in plastic greenhouses without side film also remained above 7.5. A phenological shift or the use of a superior-colored cultivar would be effective as long-term adaptation measures.

Key words: Covered cultivation, Full-flowering date, Global warming, Plastic greenhouse, Poor skin color

1. Introduction

Because perennial crops have narrower adaptability to climate than annual crops, fruit trees are considered particularly vulnerable to climate change (MAFF, 2015). Warming temperatures are already worldwide affecting the phenology of several kinds of fruit tree species. (Nemani et al., 2001; Menzel, 2003; Fujisawa and Kobayashi, 2010) and fruit quality (Sugiura et al., 2013) in perennial horticultural crops.

Because air temperature is the primary climatic factor affecting grape quality (Hall and Jones, 2009; Fraga et al., 2012; Mozell and Thach, 2014), increases in air temperature will have a considerable effect on grape production. Future changes in suitable land (Malheiro et al., 2010; Nemoto et al., 2016), yield (Bindi et al., 1996; Schultz, 2000; Lobell and Field, 2011), and berry quality (Jones et al., 2005; Webb et al., 2008) have been estimated for grape; however, most of those studies were on wine grapes and there have been few studies on table grapes. ‘Kyoho’ is the first and ‘Pione’ is the third most common table grape cultivar in Japan (Yamada and Sato, 2016). These cultivars are similar in appearance and have black berries at maturity.

Because high air temperatures lead to poor-color grape berries (Kobayashi et al., 1967; Kliewer, 1970; Downey et al., 2006; Shinomiya et al., 2015), an increase in the frequency of ‘Kyoho’ and ‘Pione’ grape berries with poor color has been recently observed by many grape famers in Japan (Sugiura et al., 2012, 2017). Poor skin color of black-skinned table grapes is known as “red ripening”, and such grapes have low commercial value (Kobayashi et al., 1965; Koshita et al., 2011).

Therefore, superior-color grape cultivars with high anthocyanin content in the skin, such as ‘Suzuka’ (Shinomiya et al., 2017; Shiraishi et al., 2018) and ‘Grosz Krone’ (Sato et al., 2018), have been bred in recent years. ‘Suzuka’ clearly differs from ‘Kyoho’ and ‘Pione’ in the response of berry skin color to high temperature (Sugiura et al., 2018).

Grape cultivation under cover is popular in Japan because disease incidence can be reduced by protecting plants from abundant rainfall (Nakajima, 2016). One quarter of grapes are cultivated under cover in Japan (Kamota, 1987), which may advance flowering due to higher air temperatures. The covering material is usually removed during the coloring period (Kumashiro, 2000; Nakajima, 2016). This phenological shift caused by cover may improve skin color.

In order to help grape producers understand the necessity of adaptation measures, the effectiveness must be correctly evaluated and shown. Modeling of the effect of air temperature on the skin color of staple and superior-color cultivars has been
reported for Japan (Sugiura et al., 2018). Here, we proposed a
statistical model to estimate the phenological shifts. Using these
model, we predicted deterioration in skin color of table grapes
and evaluated the effects of the phenological shift and the use of
a superior-color cultivar as adaptation measures.

2. Materials and methods

2.1 Full-flowering date data

Data on the full-flowering dates of ‘Kyoho’, ‘Pione’, and
‘Suzuka’ grape cultivars in 50 experimental vineyards of
agricultural research institutes in 39 prefectures (Fig. 1, Table 1)
from 1983 to 2016 were analyzed. The grapevines were grown
in open fields (OF), under partial cover (PC), or in a plastic
greenhouse with (PS) or without side film (PH) for the National
Trial of Grapes for regional adaptability.

Cultivation under PC, in which part of the roof is covered
with plastic film, is known as “simple cover cultivation” or “tunnel
cultivation” in Japan. The whole roof is covered with plastic film
in a plastic greenhouse. A PH is known as a “rain shelter” and a
PS is known as an “unheated plastic greenhouse”.

In the trial, the full-flowering date was defined as the date
when more than 80% of all flower clusters were open in more than 80% of
all flower clusters (NIFTS, 2007).

2.2 Climate data

As the actual air temperatures, we used the daily mean air
temperatures in the AMeDAS mesh dataset (Seino, 1993), a
climate dataset with 1-km resolution (each grid cell measures
45° in longitude × 30° in latitude) based on statistics from meteorological observation stations of the Japan Meteorological
Agency across Japan from 1978 onward.

Projected air temperatures of each grid cell was obtained
from a climate dataset (hereafter “the NIAES 2015 dataset”).
This dataset was developed by the National Institute for
Agro-Environmental Sciences (NIAES), Japan, using climate change scenarios derived from global climate models (GCMs)
with 1-km resolution and covering 1981–2100 (Ishigooka et al.,
2017). In this study, we used the monthly mean air temperature
data calculated by five GCMs (MIROC5, MRI-CGCM3,
GFDL-CM3, CSIRO-Mk3-6-0, and HadGEM2-ES) simulated
for three emission scenarios of representative concentration pathways (RCP2.6, low; RCP4.5, moderate; RCP8.5, high) in the
NIAES 2015 dataset.

Monthly increases in temperature in each grid cell for
2001–2020 relative to 1981–2000 (the 20-year baseline period)
were calculated as the difference between the 20-year average
of monthly mean air temperatures during 2001–2020 and during
1981–2000 obtained from the NIAES 2015 dataset. Projected
daily mean air temperatures of each grid cell during 2001–2020
were calculated as the sum of daily mean air temperatures
during 1981–2000 in AMeDAS mesh data and each monthly increase in temperature during 2001–2020. Projected daily
mean air temperatures during 2021–2040 were determined as the
sum of daily mean air temperatures during 1981–2000 in AMeDAS mesh data and each monthly increase in temperature
during 2021–2040. Projected daily mean air temperatures after
2041 were determined similarly as the sum of daily mean air
temperatures during 1981–2000 in AMeDAS mesh data and
each monthly increase in every 20-year period afterwards from
the NIAES 2015 dataset.

In the simulation described in subsection 2.4 and 2.5, we used
the actual daily mean air temperatures from 1981 to 2017 and
the projected daily mean air temperatures from 2018 to 2100.

2.3 Development of a model to estimate full-flowering date

The relationship between the observed full-flowering dates in 50 vineyards (Fig. 1, Table 1) and air temperature were statistically modeled to develop an equation to estimate
full-flowering date. In this model, the full-flowering date is
shown as the day of year (DOY), i.e. the number of days from
January 1. Daily mean air temperatures in the AMeDAS mesh
dataset were used as the air temperatures at each vineyard.

2.4 Simulation of full-flowering date and skin color

Out of the 50 vineyards, a representative point in each
prefecture was selected (Fig. 1, Table 1), and the full-flowering
date and skin color of the 39 selected vineyards in 1981–2100
were estimated. The following equations (Sugiura et al.,
2018) were used for estimating the skin color rating in each
year. The skin color rating (0 = green to 12 = black) is a value
on a standardized color chart (Yamazaki and Suzuki, 1980)
that is used to visually assess the skin color of purple- and
black-skinned grapes.

\[
SC('Kyoho') = -0.959 \times Tm(59-92DAF) + 33.9
\]

\[
SC('Pione') = -1.053 \times Tm(46-91DAF) + 35.3
\]

\[
SC('Suzuka') = -0.655 \times Tm(52-93DAF) + 26.6
\]
Table 1. Location of experimental vineyards, periods of observation, and the number of full-flowering date data points.

| No. | Prefecture | N(°) | E(°) | Periods | ‘Kyoho’ | ‘Pione’ | ‘Suzuka’ | n° |
|-----|------------|------|------|---------|---------|---------|---------|----|
| 1   | Hokkaido   | 43.05| 141.76| 2000–2016 | 14 | 8 | 3 |
| 2   | Aomori     | 40.50| 141.33| 2001–2016 | 11 | 9 | 0 |
| 3   | Aomori     | 40.65| 141.35| 1987–1990 | 4 | 0 | 0 |
| 4   | Aomori     | 40.63| 140.62| 2001–2008 | 8 | 3 | 0 |
| 5   | Iwate      | 39.35| 141.11| 2000–2016 | 12 | 8 | 0 |
| 6   | Iwate      | 39.47| 141.29| 1987–1995 | 6 | 0 | 0 |
| 7   | Miyagi     | 38.17| 140.85| 1988–2016 | 17 | 4 | 0 |
| 8   | Akita      | 39.86| 140.02| 1983–2008 | 19 | 6 | 0 |
| 9   | Akita      | 39.24| 140.53| 2012–2016 | 4 | 5 | 0 |
| 10  | Yamagata   | 38.35| 140.28| 1988–2016 | 24 | 8 | 0 |
| 11  | Fukushima  | 37.81| 140.45| 1998–1999 | 1 | 0 | 0 |
| 12  | Ibaraki    | 36.27| 140.33| 1989–2016 | 19 | 13 | 0 |
| 13  | Tochigi    | 36.61| 139.87| 1989–2016 | 16 | 6 | 4 |
| 14  | Gunma      | 36.34| 139.23| 2012–2016 | 5 | 0 | 0 |
| 15  | Saitama    | 36.08| 139.64| 1989–2016 | 12 | 10 | 0 |
| 16  | Tokyo      | 35.70| 139.40| 1988–2016 | 20 | 10 | 0 |
| 17  | Kanagawa   | 35.55| 139.28| 1996–2016 | 16 | 9 | 0 |
| 18  | Kanagawa   | 35.30| 139.26| 1897–1991 | 5 | 0 | 0 |
| 19  | Yamanashi  | 35.70| 138.67| 1998–2016 | 18 | 9 | 4 |
| 20  | Yamanashi  | 35.68| 138.68| 1997–2016 | 18 | 9 | 4 |
| 21  | Nagano     | 36.66| 138.31| 1987–2016 | 24 | 5 | 3 |
| 22  | Nagano     | 36.10| 137.94| 1987–2003 | 13 | 0 | 0 |
| 23  | Niigata    | 37.98| 139.30| 1987–2016 | 22 | 8 | 0 |
| 24  | Toyama     | 36.82| 137.43| 1989–2016 | 19 | 8 | 0 |
| 25  | Ishikawa   | 36.71| 136.70| 1988–2016 | 24 | 10 | 6 |
| 26  | Aichi      | 35.16| 137.07| 1987–2016 | 23 | 9 | 0 |
| 27  | Mie        | 34.70| 136.14| 1988–2016 | 21 | 8 | 4 |
| 28  | Shiga      | 34.99| 136.01| 1991–2016 | 17 | 9 | 0 |
| 29  | Kyoto      | 35.67| 135.10| 2001–2012 | 6 | 4 | 1 |
| 30  | Kyoto      | 34.81| 135.78| 1988–1996 | 6 | 0 | 0 |
| 31  | Osaka      | 34.53| 135.60| 1989–2016 | 14 | 1 | 3 |
| 32  | Hyogo      | 34.91| 134.90| 1989–2016 | 14 | 8 | 2 |
| 33  | Nara       | 34.32| 135.73| 1996–2016 | 15 | 8 | 3 |
| 34  | Nara       | 34.50| 135.79| 1988–1995 | 5 | 0 | 0 |
| 35  | Tottori    | 35.47| 133.75| 2006–2016 | 3 | 8 | 4 |
| 36  | Tottori    | 35.49| 133.82| 1989–2003 | 11 | 0 | 0 |
| 37  | Shimane    | 35.33| 132.73| 1985–2016 | 17 | 11 | 4 |
| 38  | Okayama    | 34.78| 134.02| 1987–2016 | 21 | 10 | 0 |
| 39  | Hiroshima  | 34.33| 132.83| 1988–2016 | 29 | 11 | 4 |
| 40  | Hiroshima  | 34.33| 132.82| 1988–2016 | 24 | 10 | 4 |
| 41  | Yamaguchi  | 34.16| 131.53| 1989–2016 | 19 | 9 | 4 |
| 42  | Tokushima  | 34.14| 134.43| 1990–2016 | 19 | 9 | 2 |
| 43  | Kagawa     | 34.30| 133.94| 1988–2016 | 19 | 9 | 3 |
| 44  | Ehime      | 33.88| 132.81| 2011–2016 | 6 | 6 | 6 |
| 45  | Kochi      | 33.54| 133.49| 1988–1991 | 4 | 0 | 0 |
| 46  | Fukuoka    | 33.50| 130.57| 1988–2016 | 29 | 13 | 11 |
| 47  | Kumamoto   | 32.64| 130.72| 1988–2003 | 10 | 0 | 0 |
| 48  | Oita       | 33.54| 131.73| 1987–2016 | 24 | 9 | 0 |
| 49  | Miyazaki   | 32.00| 131.46| 1997–2016 | 13 | 8 | 3 |
| 50  | Kagoshima  | 31.87| 130.34| 1989–2016 | 17 | 9 | 6 |

1 Numbers correspond to the locations shown in Fig. 1. The bold numbers show representative points of each prefecture.
2 Prefecture, latitude and longitude where the experimental vineyard was located.
3 Years when the full-flowering dates were recorded.

where SC is the skin color rating of the cultivar in parentheses. 

2.5 Simulation of geographical distribution of the frequency of poor-skin color occurrence years

The skin color ratings of ‘Kyoho’, ‘Pione’, and ‘Suzuka’ in 1981–2000, 2031–2050, and 2081–2100 were simulated from the daily mean air temperatures in all grid cells (subsection 2.2), the model to estimate full-flowering date (subsection 2.3), and equations (1)–(3). Assuming that the skin color rating of <7.5 represents poor skin color (Sugiura et al., 2017), the frequency of poor-skin color occurrence years in each 20-year period in each grid cell was calculated and mapped.

3. Results

3.1 Development of a model to estimate full-flowering date

A strong negative correlation was found between the full-flowering dates of all three cultivars tested and the mean temperature in April and May (Fig. 2, Table 2). The full-flowering date depended on the cover type and became later in ‘Kyoho’ and ‘Pione’ in the following order: OF, PC, PH, and PS. As a model to estimate the full-flowering date, a regression equation was determined between the full-flowering date of each cultivar and the mean temperature in April and May. At the mean

![Fig. 2](image-url)
temperature of 15°C in April and May, the full-flowering date of ‘Kyoho’ was advanced by 2.3 days in PC, 5.6 days in PH, and 17.9 days in PS in comparison with OF.

Because the number of data points for the full-flowering date of ‘Suzuka’ was small in OF (n = 8) and PS (n = 14), the relationship between the full-flowering date and air temperature could not be analyzed. In the same vineyard in the same year, the full-flowering date of ‘Suzuka’ was 0.6 days later than that of ‘Kyoho’ in OF (n = 7) and 0.9 days earlier than that of ‘Kyoho’ in PS (n = 9); however, these differences were small and not significant. Therefore, the full-flowering date of ‘Suzuka’ can be regarded as almost the same as that of ‘Kyoho’.

### 3.2 Estimated full-flowering date and skin color

The average decadal mean air temperature in the 39 prefectures from 1981–1990 to 2091–2100 is shown in Figure 3. It rose gradually, and the 20-year average temperature was higher by 1.7°C (RCP4.5), 1.5°C (RCP2.6), or 1.9°C (RCP8.5) in 2031–2050 than in 1981–2000. The standard deviations (SDs) between GCMs were 0.56, 0.61, 0.61°C respectively. The difference due to the different emission scenarios increased after around 2040, and the average temperature in 2081–2100 was 2.8°C (RCP4.5), 1.9°C (RCP2.6), or 5.0°C (RCP8.5) higher than in 1981–2000. The SDs between GCMs were 0.74, 0.59, 0.99°C respectively.

In OF, the full-flowering date of ‘Kyoho’ averaged over the 39 prefectures gradually advanced (Fig. 4). The average full-flowering date was 158 DOY during 1981–2000, about 9 days (SD between GCMs was about 2.9 days) earlier in 2031–2050, and 14 (RCP4.5), 10 (RCP2.6), or 25 (RCP8.5) days (SD were 3.0, 2.2, 4.4 days respectively) earlier in 2081–2100.

Under cover, the full-flowering dates of ‘Kyoho’ averaged over the 39 prefectures were 152 DOY (PH) and 140 DOY (PS) in 1981–2000 (data not shown). Under the RCP4.5 scenario, they advanced to 143 DOY (PH) and 131 DOY (PS) in 2031–2050, and to 137 DOY (PH) and 125 DOY (PS) in 2081–2100.

In OF, the skin color rating of ‘Kyoho’ averaged over the 39 prefectures gradually declined from 9.4 in 1981–2000 to 7.9 (SD was 0.56) in 2031–2050 and to 7.0 (SD was 0.73) in 2081–2100 under RCP4.5 (Fig. 5A). The difference due to the emission scenarios was small before around 2040 but increased afterwards. Skin color rating decreased to 5.7 (SD was 0.68) in 2081–2100 under RCP8.5.
The changes in the skin color rating of the three cultivars grown under cover averaged over the 39 prefectures under RCP4.5 are shown in Figure 5B. The average skin color rating of ‘Kyoho’ was 9.4 (PH) and 9.6 (PS) in 1981–2000, very close to that in OF. In PS, it decreased to 8.7 in 2031–2050 and to 8.2 in 2081–2100; this decrease was smaller than in OF.

In PH, the skin color rating of ‘Suzuka’ gradually declined but was always higher than that of ‘Kyoho’, whereas that of ‘Pione’ was always lower than that of ‘Kyoho’.

To investigate the regional differences in skin color, the 39 prefectures were grouped into 5 regions (Fig. 1). The average air temperature in 1981–2000 was 10.3°C in northern Japan (Hokkaido–Tohoku; sites 1–11 in Table 1), 13.3°C in eastern Japan (Kanto–Hokuriku; 12–25), 14.1°C in central Japan (Tokai–Kinki; 26–34), 14.6°C in western Japan (Chugoku–Shikoku; 35–45), and 15.9°C in southern Japan (Kyushu, 46–50).

The skin color rating of ‘Kyoho’ (OF, RCP4.5) was always highest in northern Japan, second highest in eastern Japan, and lowest in southern Japan (Fig. 5C). In southern Japan, the skin color rating of ‘Kyoho’ was always higher in PS than in OF and PH, and that of ‘Suzuka’ was always higher than that of ‘Kyoho’ (Fig. 5D).

Fig. 4. Decadal estimated full-flowering dates of ‘Kyoho’ in open field averaged over 39 prefectures for each emission scenario (RCP) from the 2010s. DOY, the number of days from January 1.

Fig. 5. Decadal estimated skin color rating. (A) was shown for each emission scenario from the 2010s. (B–D) are based on the emission scenario of RCP4.5 from the 2010s. (A) ‘Kyoho’ in open field; averaged over 39 prefectures. (B) The 3 cultivars in plastic greenhouses without (PH) or with (PS) side film; averaged over 39 prefectures. (C) ‘Kyoho’ in open field in five regions (see Fig. 1). (D) ‘Kyoho’ in plastic greenhouses without (PH) or with (PS) side film or ‘Suzuka’ in PH in southern Japan.
3.3 Geographical distribution of the frequency of poor skin color

In 1981–2000, there were few areas where poor skin color in ‘Kyoho’ occurred in ≥ 20% of the years in OF (Fig. 6A), but such areas were widely distributed in the plains of all regions except northern Japan in 2031–2050 (Fig. 6B).

The frequency of poor-skin-color years for ‘Kyoho’ in PH was similar to that in OF in 2031–2050 (Fig. 6C), but that in PS was lower than that in OF in a wide area (Fig. 6D). In ‘Suzuka’, the frequency of poor-skin-color years was 20% or less in 2031–2050 in most areas (Fig. 6E). For ‘Pione’, this frequency was estimated to exceed 50% in most of the plain areas except in northern Japan in 2031–2050 (Fig. 6F).

4. Discussion

4.1 Full-flowering date

Because temperature greatly affects the full-flowering date of deciduous fruit trees, statistical models by using monthly mean temperatures have been often used for convenient flowering-date prediction on the basis of temperature (Machida, 1982; Kamata, 1992). In many cases, higher temperature leads to earlier flowering.

The full-flowering dates of both ‘Kyoho’ and ‘Pione’ were earlier in PC than in OF, but the differences were small. Those in PH were earlier than in PC and those in PS were earliest.
among all four cover types. Because the completeness of cover increases in the order of OF, PC, PH, and PS, it is clear that the air temperature also increases in this order.

The standard error of the regression equation was larger with PS and PH than OF (Table 2). This is likely to be due to a large difference between air temperatures in plastic greenhouses on account of differences in covering time, size of the roof window, and roof height, even if the outside air temperature is the same.

Grapevines exposed to inadequate chilling due to warm autumn and winter exhibit abnormal (decreased, delayed, and non-uniform) budding (Webb et al., 2007). However, chilling only for 500 h is required for breaking endodormancy in ‘Kyoho’ and ‘Pione’ (Hirose et al., 2000; Asakura, 2012). Because endodormancy of ‘Kyoho’ is already broken before December (Kubota and Miyamuki, 1992), the buds break normally even if PS is used from December (Kuroi, 1985).

The phenology may advance by up to 25 days due to warming by the end of this century (Fig. 4). The typical covering time with PS in southern Japan is late February (Miyazawa, 1987); therefore, abnormal budding would not occur even if covering time is advanced by 1 month.

Cyanamide is widely used to accelerate endodormancy breaking and to prevent abnormal budding in heated plastic greenhouses in viticulture in Japan (Iwasaki and Weaver, 1977; Kubota and Miyamuki, 1992; Kuroi, 1985). If very warm autumns delay endodormancy breaking beyond the covering time, cyanamide may be useful also in PH and PS.

4.2 Change in skin color

Crop developmental models developed for specific areas are difficult to apply to other areas. However, we consider the model to estimate skin color of grape berries adopted in this study (equations (1)–(3)) to be applicable throughout Japan because it is based on measurements in many grape-growing regions across the country.

Previous studies (Yamane and Shibayama, 2006; Barnuud et al., 2014) suggested that the temperature-sensitive period for skin coloration (when low temperature is effective in coloring) is coloring period which begins soon after veraison. Accordingly, temperature from veraison to berry maturation was used in equations (1)–(3).

High temperature in covered cultivation can advance budding and flowering; the covering material is usually removed during the coloring period to prevent inhibition of berry skin coloration (Kumashiro, 2000; Nakajima, 2016). Therefore, the projected values of external air temperature can be used to estimate skin color in covered cultivation.

The differences in predicted skin color among the emission scenarios were very large (Fig. 5A). This suggests that the timing of adopting adaptation measures (see below) differs depending on the assumed emission scenario. For example, the average skin color rating of ‘Kyoho’ in 39 prefectures for RCP 4.5 was lower than 7.5 from the 2050s (Fig. 5A). The skin color rating decreased below 7.5 from the 2040s in RCP8.5, which was earlier than in RCP 4.5, whereas that in RCP 2.6 seemed to stabilize above 7.5.

It was shown that the timing of adopting adaptation measures differs depending on the region (Fig. 5C). The skin color ratings of ‘Kyoho’ under RCP4.5 decreased below 7.5 from the 2020s in southern Japan and from the 2030s in western and central Japan, earlier than the average over the 39 prefectures. Earlier adaptation measures will be necessary in these regions. Figure 6 suggests that in the same area, earlier adaptation measures would be necessary in the plains than in the inland areas.

4.3 Effect of adaptation measures

In this study, we examined the effect of two adaptation measures, the phenological shift caused by covered cultivation and the use of a superior-colored cultivar, under the moderate emission scenario (RCP4.5). The phenological shift can delay deterioration in skin color: the skin color rating of ‘Kyoho’ averaged over the 39 prefectures decreased below 7.5 from the 2050s in OF (Fig. 5A) and from the 2070s in PH (Fig. 5B), but remained above 8 in PS even at the end of this century (Fig. 5B).

We consider the phenological shift caused by PS to be effective until the end of this century.

The phenological shift is effective in coloring because the air temperature during the coloring period drops with advancing phenology. The coloring period of ‘Kyoho’ is from 50 to 92 DAF, as shown in equation (1). Seasonal change of daily temperature averaged over the 39 prefectures and coloring period in OF and PS in 1981–2000, 2031–2050, and 2081–2100 are shown in Figure 7. The air temperature in the coloring period was not markedly different between OF and PS in 1981–2000, but the temperature differences between OF and PS would increase in 2031–2050 and 2081–2100 (Fig. 7), making the effect of the phenology shift clearer.

The skin color rating of ‘Suzuka’ remained above 8 even at the end of this century (Fig. 5B). Therefore, we consider that
replanting to the superior-colored cultivar as well as introduction of PS is effective long-term adaptation measures. Because the skin color rating of ‘Pione’ decreased below 7.5 in the 2020s, adaptation measures would be needed for ‘Pione’ earlier than for ‘Kyoho’.

The skin color rating of ‘Kyoho’ in PS and ‘Suzuka’ in PH remained above 7.5 at the end of this century even in southern Japan, where the impact of warming appears to be remarkable (Fig. 5D). We conclude that the use of a superior-colored cultivar and a phenological shift achieved by the introduction of PS would be effective over a long term even in southern Japan. On the basis of the data in Figure 6, grape producers can judge the necessity of adaptation measures in their production areas.

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References
Asakura T, 2012: Modeling temperature responses of fruit trees for assessing the impact of climate warming. Research for Tropical Agriculture 5, 143–146.

Barnuud NN, Zerihun A, Gibberd B, Bates B, 2014: Berry composition and climate: Responses and empirical model. International Journal of Biometeorology 58, 1207–1223.

Bindi M, Ibbi L, Gozzini B, Orlandini S, Miglietta F, 1996: Modelling the impact of future climate scenarios on yield and yield variability of grapevine. Climate Research 7, 213–224.

Downey MO, Dokoozlian NK, Krsitc MP, 2006: Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: a review of recent research. American Journal of Enology and Viticulture 7, 257–268.

Friga H, Malheiro AC, Moreira PB, Santos JA, 2012: An overview of climate change impacts on European viticulture. Food Energy Security 1, 94–110.

Fujisawa M, Kobayashi K, 2010: Apple (Malus pumila var. domestica) phenology is advancing due to rising air temperature in northern Japan. Global Change Biology 16, 2651–2660.

Hall A, Jones GV, 2009: Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. Australian Journal of Grape and Wine Research 15, 97–119.

Hirose M, Kakuda Y, Fujita Y, Watanabe H, Yasuno T, Ozeki Y, Nakao S, 2000: Chilling requirement and chemical treatment for breaking dormancy in grapevines, peaches and Japanese pears. Bulletin of the Oita Prefectural Agricultural Research Center 30, 1–13.

Ishigooka Y, Fukui S, Hasegawa T, Kuwagata T, Nishimori M, Kondo M, 2017: Large-scale evaluation of the effects of adaptation to climate change by shifting transplanting date on rice production and quality in Japan. Journal of Agricultural Meteorology 73, 156–173.

Iwaseki K, Weaver RJ, 1977: Effects of chilling, calcium cyanamide, and bud scale removal on bud break, rooting, and inhibitor content of buds of ‘Zinfandel’ grape (Vitis vinifera L.). Journal of the American Society for Horticultural Science 102, 584–587.

Jones GV, White MA, Cooper OR, Storchmann K, 2005: Climate change and global wine quality. Climatic Change 73, 319–343.

Kamata S, 1992: Effects of meteorological factors on flowering day of apple. Journal of the Japanese Society for Horticultural Science 61, 17–24.

Kamota F, 1987: Protected cultivation of fruit trees in Japan. Journal of Agricultural Meteorology 42, 391–395.

Kliewer WM, 1970: Effect of day temperature and light intensity on coloration of Vitis vinifera L. grapes. Journal of the American Society for Horticultural Science 45, 693–697.

Kobayashi A, Fukushima T, Nii N, Harada K, 1967: Studies on the thermal conditions of grapes. VI. Effects of day and night temperature on yield and quality of Delaware grapes. Journal of the Japanese Society for Horticultural Science 36, 373–379.

Kobayashi A, Yukinaga H, Itano T, 1965: Studies on the thermal conditions of grapes. III. Effects of night temperature at the ripening stage on the fruit maturity and quality of Delaware grapes. Journal of the Japanese Society for Horticultural Science 34, 26–32.

Koshita Y, Yamane T, Tsuchishii H, Azuma A, Mitani N, 2011: Regulation of skin color in ‘Aki Queen’ grapes: Interactive effects of temperature, girdling, and leaf shading treatments on coloration and total soluble solids. Scientia Horticulturae 129, 98–101.

Kubota N, Miyamuky M, 1992: Breaking bud dormancy in grapevines with garlic paste. Journal of the American Society for Horticultural Science 117, 898–901.

Kumashiro K, 2000: Protected cultivation (grape), In Basic Seminar on Agriculture. Fruit cultivation basic, Rural Culture Association, Tokyo, pp. 253–259.

Kuroi I, 1985: Effects of calcium cyanamide and cyanamide on bud break of ‘Kyoho’ grape. Journal of the Japanese Society for Horticultural Science 54, 301–306.

Lobell DB, Field CB, 2011: California perennial crops in a changing climate. Climatic Change 109, 317–333.

Machida Y. 1982: Maps of bloom and harvest date in usual year for Japanese pear (Pyrus serotina Rehd. var. culta) Cultivar ‘Shinsui’, ‘Kosui’ and ‘Hosui’.Bulletin of the Fruit Tree Research Station A9, 25–42.

Malheiro AC, Santos JA, Fraga H, Pinto JG, 2010: Climate change scenarios applied to viticultural zoning in Europe. Climate Research 43, 163–177.

Menzel A, 2003: Plant phenological anomalies in Germany and their relation to air temperature and NAO. Climatic Change 57, 243–263.

Ministry of Agriculture, Forestry and Fisheries (MAFF), 2015: Climate Change Adaptation Plan of MAFF. MAFF, Tokyo, pp. 1–38. http://www.maff.go.jp/j/kanko/kanko/iseikai/pdf/pdf/tekiou_eng.pdf

Miyazawa M, 1987: Tendencies in Protected cultivation of grape and business issues. Japanese Journal of Farm Management 24, 16–27.

Mozell MR, Thach L, 2014: The impact of climate change on the global wine industry: Challenges & solutions. Wine Economics and Policy 3, 81–89.

Nakajima Y, 2016: Cover removal and temperature in simple covered cultivation, In The latest agricultural technology. Fruit
T. Sugiura *et al.*: Deterioration in skin color of table grape due to climate change and effects of adaptation measures

Trees vol. 9. Rural Culture Association, Tokyo, pp. 151–154.
NARO Institute of Fruit Tree Science (NIFTS), 2007: Evaluation methods in national trial of selections and standard varieties, NARO, Tsukuba, pp. 233.

Nemoto M, Hirotta T, Sato T, 2016: Prediction of climatic suitability for wine grape production under the climatic change in Hokkaido. *Journal of Agricultural Meteorology* 72, 167–172.

Sato A, Yamada M, Mitani N, Kono A, Ban Y, Ueno T, Shiraishi M, Onoue N, Iwanami H, Azuma A, Yoshioka M, Mase N, Ito T, 2018: A new grape cultivar, ‘Grosz Krone’. *Horticultural Research (Japan)* 17 (Suppl. 1), 296.

Shultz HR, 2000: Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Australian Journal of Grape and Wine Research* 6, 2–12.

Seino H, 1993: An estimation of distribution of meteorological elements using GIS and AMeDAS data. *Journal of Agricultural Meteorology* 48, 379–383.

Shinomiya R, Fujishima H, Muramoto K, Shiraishi M, 2015: Impact of temperature and sunlight on the skin coloration of the ‘Kyoho’ table grape. *Scientia Horticulturae* 193, 77–83.

Shinomiya R, Shiraishi M, Hirakawa N, Ibi A, Fujishima H, Chijiwa H, Muramoto K, 2017: A new grape cultivar ‘Suzuka’. *Bulletin of the Fukuoka Agriculture and Forestry Research Center* 3, 36–42.

Shiraishi M, Shinomiya R, Chijiwa H, 2018: Varietal differences in polyphenol contents, antioxidant activities and their correlations in table grape cultivars bred in Japan, *Scientia Horticulturae* 227, 272–277.

Webb LB, Whetton PH, Barlow EWR, 2007: Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research* 13, 165–175.

Webb LB, Whetton PH, Barlow EWR, 2008: Climate change and winegrape quality in Australia. *Climate Research* 36, 99–111.

Yamane T, Shibayama K, 2006: Effects of changes in the sensitivity to temperature on skin coloration in ‘Aki Queen’ grape berries. *Journal of the Japanese Society for Horticultural Science* 75, 458–462.

Yamazaki T, Suzuki K, 1980: Color charts: useful guide to evaluate the fruit maturation. *Bulletin of the Fruit Tree Research Station* A4, 19–44.