THREE CLIMATE CHANGE ADAPTATION STRATEGIES FOR FRUIT PRODUCTION

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ABSTRACT

As perennial crops have less adaptability to climate than annual crops, fruit trees are considered vulnerable to climate change. The general effects of global warming can be estimated by collecting and analyzing current fruit tree productivity, in terms of the recent rise in temperature. Therefore, surveys of the public institutes of fruit tree research in 47 prefectures were conducted. The results suggested that recent warming trends have already significantly affected nearly all types of fruit tree species, and have caused many kinds of problems, such as poor skin color in apple, grape, and citrus due to pigment synthesis inhibition; peel puffing in satsuma mandarin; dead flower buds in Japanese pear; freezing injury of Japanese chestnut due to reduced freezing tolerance; incomplete endodormancy in the heated cultivation of Japanese pear; and frost damage due to early flowering of apple. In addition, data analysis of long-term observations has provided evidence that the taste of apples has changed. Our strategy to address climate change adaptation in fruit production is split into three stages. The stage 1 is adaptation measures using production technology to utilize the trees that are currently being cultivated. The stage 2 is replanting production areas with cultivars that are better adapted to global warming, and the stage 3 is to move the production areas. For the stage 1, we have investigated the mechanisms of damage occurrence and developed adaptation measures, such as girdling to improve the skin coloration of grapes, changing the timing of fertilizer application to decrease the occurrence of dead flower buds in Japanese pear in open fields, and the adoption of technologies to decrease sunburn of fruit and to decrease peel puffing in satsuma mandarin. As fruit trees are only replanted once in about 30 years, it is difficult to introduce a new cultivar; however, new cultivars adapted to warming have been developed, such as superior-colored cultivars of grape ("Gross Krone," *"Queen Nina"), a yellow cultivar of apple without coloring problems*

("Morinokagayaki"), a Japanese pear cultivar resistant to dead flower buds ("Rinka"), a citrus resistant to peel puffing ("Mihaya"), and a peach cultivar with a low chilling requirement ("Sakuhime"). For the stage 3, the movement of production areas, we have created predictive maps showing suitable growing areas for various fruit trees for the future, for producers and local governments. Maps of future suitable areas for orchards have been developed for apple satsuma mandarins, which are the most common fruit trees in Japan, and for tankans, which are subtropical citrus fruits.

Keywords: Cultivar, fruit sunburn, global warming, poor skin color, suitable area

INTRODUCTION

Climate change affects agriculture significantly, and adaptation measures must be developed as countermeasures against the risks to agricultural productivity worldwide (IPCC, 2014). A temperature increases of 1.2 ºC has been observed over the past 100 years in Japan (JMA, 2018). Considering that the development of cultivars and fruit cultivation technology has undergone major improvements in Japan over the past century, it is difficult to identify the impacts of temperature increase on agricultural productivity by comparing conditions between now and 100 years ago. Looking at changes in average temperature in Japan since the 1970s, major changes have occurred from the end of the 1980s onward. Mean temperatures from 1990 onward are approximately 0.7 ºC higher than the mean temperature between 1970 and 1989.

As perennial crops have less adaptability to climate than annual crops, fruit trees are considered particularly vulnerable to climate change (MAFF, 2015). Already, the effects of global warming on fruit tree productivity in Japan are apparent. This report covers assessments of global warming impacts on fruit tree production in the past and future, and the countermeasures that Japan has developed and will develop in the future.

CLIMATE CHANGE EFFECTS ON FRUIT TREES

Current fruit damage

In order to develop climate change adaptation measures, scientific impact assessment is a prerequisite. The general effects of climate change can be estimated by collecting and analyzing data from various agricultural systems on production changes due to this recent temperature rise.

Therefore, the National Agriculture and Food Research Organization carried out a survey of already-manifested impacts of warming on agriculture in all 47 prefectures of Japan (Sugiura *et al*., 2012). All prefectures reported at least one phenomenon caused by warming with respect to fruit trees (Fig. 1). This clearly demonstrated that the impacts of warming have spread across the entire country with respect to the fruit tree industry.

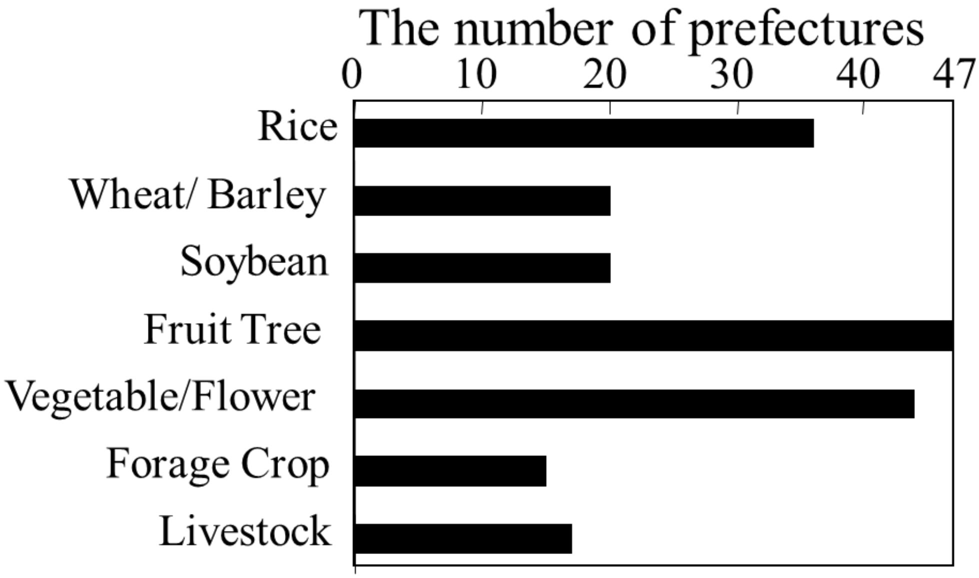

Fig. 1. Number of prefectures reporting at least one change in different sectors of agricultural production caused by recent warming.

The survey suggested that recent warming trends have already significantly affected nearly all types of fruit tree species, and the tree species can be classified into two types based on the responses of fruit development to recent warming (Fig. 2; Sugiura *et al.,* 2007). The first group is the earlier developing type and the second is the prolonged development type.

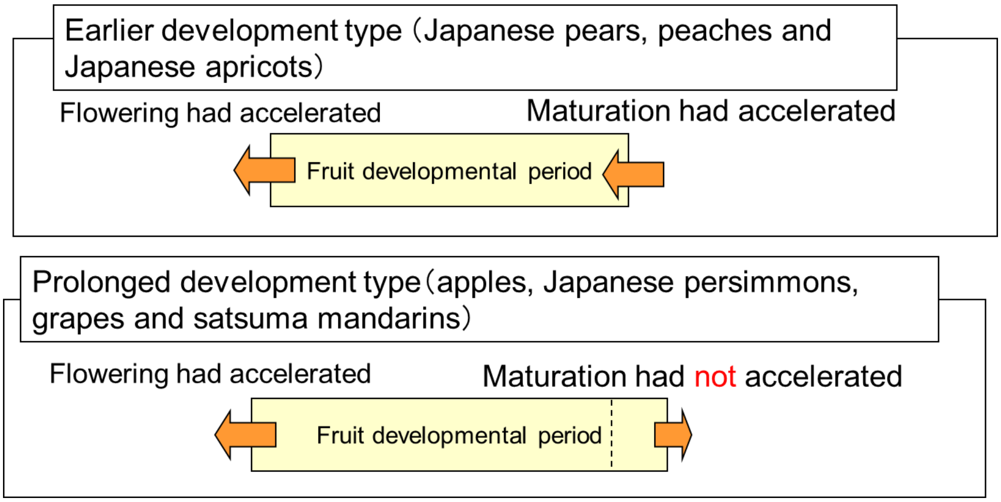

Fig. 2. Tree species have been classified into two types based on the responses of fruit development to recent warming trends.

The "earlier development" type includes those tree species in which both flowering and harvesting periods had accelerated; these include Japanese pears, peaches, and Japanese apricots. The "prolonged development" type includes those tree species in which the flowering period had accelerated, but not the harvesting period; this type includes apples, Japanese persimmons, grapes, and satsuma mandarins.

Phenological and physiological changes

The most important and common impact of warming on fruit trees is the delayed and poor coloring of fruit skin. Poor coloration reduces marketability. The normal development of the coloring of apples and grapes is brought about by the loss of chlorophyll and the synthesis of anthocyanins, and these processes occur rapidly under low-temperature conditions. We investigated the relationship between skin color and air temperature in grape production areas of 18 prefectures. When the mean air temperature during the 40 days before harvest date was ≥24°C, the skin color ratings (the higher the color rating, the stronger the coloration) of "Kyoho," "Pione," and "Suzuka" grape were significantly negatively correlated with air temperature (Sugiura *et al.*, 2018). The skin color ratings decreased by about 1 unit per 1°C increase (Fig. 3). Temperatures of 25°C or lower are appropriate for the synthesis of anthocyanins in apples (Arakawa, 1991).

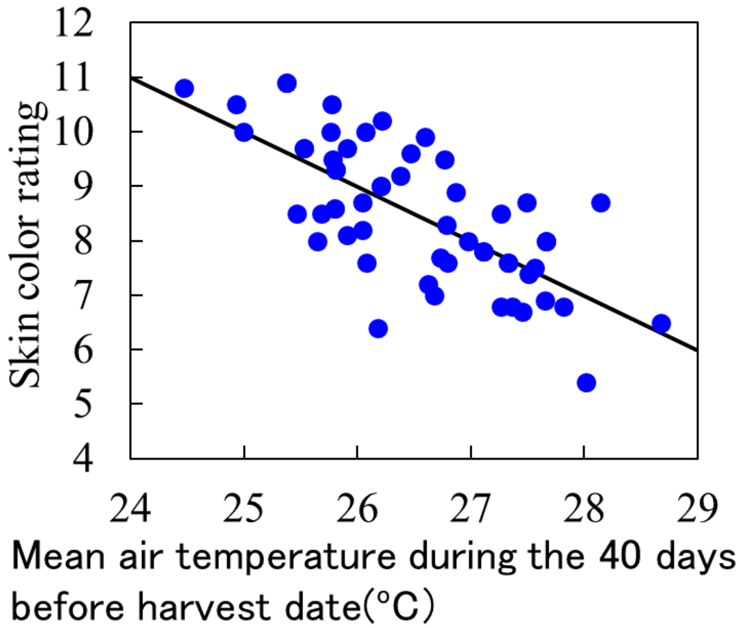

Fig. 3. The relationship between the skin color rating of "Kyoho" grape at harvest and the mean air temperature during the 40 days before the harvest date. Linear regression at air temperatures ≥24°C is shown.

A similar principle applies to carotenoid accumulation, which turns citrus and Japanese persimmons yellow and bright red, respectively. Therefore, if temperatures increase due to global warming during the color development stage, the coloring of the fruit will be adversely affected.

If flowering accelerates as a result of warming, it can be expected that the harvest time will also accelerate. In reality, the harvest dates for Japanese pears, peaches, etc. are indeed tending to be earlier as a result of warming. However, among fruits, such as apples and Japanese persimmon, in which pigment development is an important indicator in determining the time of harvest, since high temperatures impede coloration, the harvest date remains unchanged even if the flowering date is accelerated. In such cases, the development period of the fruit, that is, the number of days from flowering to harvest, will actually increase. The harvesting period of fruit of the prolonged development type is often determined by the degree of coloring, so the delay in skin coloring under elevated temperatures is the reason why the harvesting period of this type has not accelerated.

Changes in fruit quality traits, such as fruit enlargement, peel puffing (Fig. 4), reduction of acid concentration, reduction of soluble tannin concentration of Japanese persimmon, softening of fruit flesh, and tendency to spoil rapidly, might all be associated with the increment in the fruit development period. Therefore, most of these changes in fruit quality are more noticeable in the prolonged development type fruits than in the earlier development type fruits.

Based on records covering 30–40 years, we obtained evidence that the taste and textural attributes of apples have changed as a result of warming (Fig. 5; Sugiura *et al*., 2013). Decreases in acid concentration, fruit firmness, and watercore development were observed regardless of the maturity index used for the harvest date (e.g., calendar date, number of days after full bloom, peel color, and starch concentration); all such changes may have resulted from earlier blooming and higher temperatures during the maturation period. These results suggest that the qualities of apples on the market are undergoing long-term changes.

Fig. 4. Peel puffing in satsuma mandarin (left-hand picture). The right-hand picture shows a normal fruit.

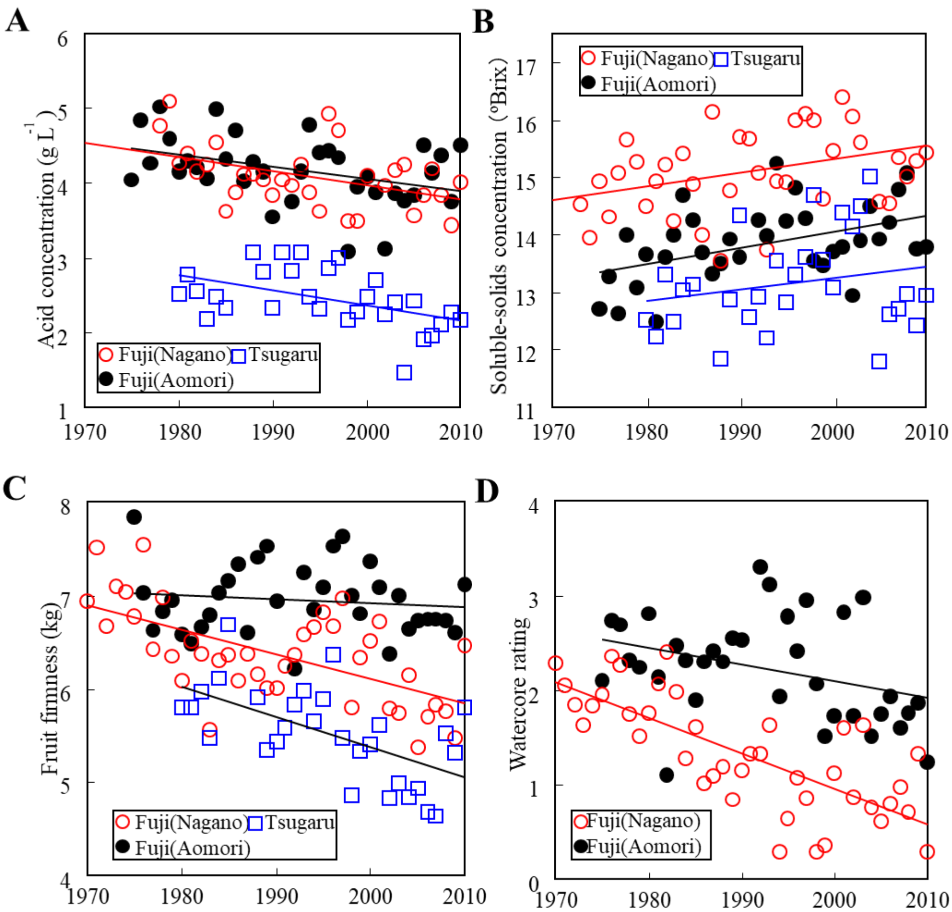

Fig. 5. Changes in the taste and textural attributes of apples over a 40-year period. Time series of (A) acid concentration, (B) soluble-solids concentration, (C) fruit firmness, and (D) watercore rating recorded on November 1 ("Fuji") or September 1 ("Tsugaru"). Lines represent linear regressions.

When the flower buds of deciduous fruit trees are exposed to insufficient numbers of hours at low temperatures during the endodormancy period, it is possible that germination disorders will arise in the spring. This is a far more serious problem in forcing cultures, where heating is commenced during the low-temperature period, than in open-field cultures. Flowering disorders occur frequently in heated plastic greenhouses that grow Japanese pears in southern Japan such as Kyushu.

Meteorological disasters

Warming also leads to meteorological disasters. Sunburn is a disorder where the skin of the fruit turns brown as a result of extremely high temperatures (Fig. 6). This symptom tends to occur in those parts of the fruit that are exposed to sunlight; however, the cause is associated more with a temperature increase rather than with the rays of sunlight. Those parts of the fruit that are exposed to the sun in the afternoon (west side) are more prone to scorching damage than those exposed during the morning when temperatures are lower.

Fig. 6. Sunburn of an apple (left-hand photo) and a citrus fruit (right-hand photo).

Despite a dramatic increase in mild winters as a result of global warming, freezing damage, such as dead flower buds in Japanese pear (Ito *et al*., 2018) and winter-kill of young Japanese chestnut trees (Sakamoto *et al*., 2015a, 2015b), has increased in deciduous fruit trees. If temperatures remain high from fall to the start of winter, fruit trees are slow to acquire cold tolerance and struggle to attain their peak cold tolerance, making them prone to freezing damage when exposed to severe cold at the start of winter and during the midwinter season. In particular, cold tolerance cannot be acquired when defoliation is delayed and new tree tops is continuing to produce new leaves under relatively high temperatures. Even after peak cold tolerance has been attained, it can temporarily decline if warm temperatures subsequently occur for three or four days, thereby increasing the risk of freezing damage.

Since warming leads to an acceleration of the flowering period, if flowering occurs too early and the period from bud break to young fruit then overlaps with the frost season, there is a higher incidence of frost damage and a potentially serious decrease in fruit production (Asakura *et al*., 2011).

ADAPTATION OF FRUIT TREES TO CLIMATE CHANGE

Our strategy to address climate change adaptation in fruit production is split into three stages. The stage 1 is adaptation measures using production technology to utilize the trees that are being cultivated now. Most of the adaptation measures currently being undertaken belong in this stage 1, which includes methods to avoid high temperatures and methods to increase high-temperature tolerance. The stage 2 of adaptation is replanting with cultivars that are better adapted to warming, and the stage 3 is to move the production areas.

Avoidance of high temperatures (stage 1)

One method to reduce the temperature of fruit is to limit the amount of fruit exposure to sunlight. Methods to prevent sunburn include using shading materials (Fig. 7) or fruit bags with high shielding performance and having numerous shoots in order to block out direct sunlight, especially the west sun. Regarding citrus fruits, thinning (or removal) of fruit near the surface and near the top of trees is an effective method to prevent sunburn and peel puffing.

Fig. 7. Use of shading materials to prevent sunburn of fruit. The right picture shows the material to avoid only the western sun.

By reducing the temperature of entire trees, it is also possible to reduce the temperature of fruit. Among fruit species such as grapes that develop color before midsummer, the coloring period can be induced under low-temperature conditions by forcing cultivation in plastic greenhouses (Sugiura et al, 2019). This is an extremely effective technique to develop better color in the berries.

When trees are exposed to water stress, the stomata on fruits and leaves close, causing an inhibition of transpiration; as a consequence, the latent heat of vaporization cannot be relieved, and the temperature of the fruit and the trees increases. Accordingly, it is important to irrigate the soil to prevent soil from drying during periods when there is risk of fruit sunburn.

Tolerance of high temperatures (stage 1)

The chemical structure of anthocyanins, which are the main pigments causing the red to black colors in fruits such as apples and grapes, include a short chain of sugar molecules, created by photosynthesis and that are stored in the fruit as sugars. Therefore, when there are a lot of photosynthates, such as after a sunny summer, this facilitates the synthesis of anthocyanins even if temperatures are high, making it easier for fruits to develop color. The amount of photosynthesis can be increased by laying reflective mulch under the fruit trees in fields to increase the amount of light striking the trees.

Increasing the amount of photosynthesis in trees is not easy. Another method to boost the sugar content of each fruit without increasing photosynthesis is to reduce the number (“thinning”) of fruits per tree. By doing this, photosynthate competition between fruits within a cluster is reduced, thereby resulting in increased sugar content in each fruit. Although this method entails some sacrifice in terms of yield, it is particularly effective in the case of grape.

Girdling (Fig. 8) is a technique to increase fruit coloration by boosting the photosynthates in fruits without reducing the number of fruits per tree (Yamane and Shibayama, 2006; Koshita *et al.,* 2011). This technique entails peeling bark off the trunk before the fruit starts developing color. The photosynthates produced in leaves are distributed upward and downward to fruits, branches, trunks, and roots through phloem sieve tubes, which lie just beneath the bark. When girdling is carried out, because the sieve tubes in the phloem also peel off with the bark, the photosynthates produced in the leaves are not distributed to the lower parts of the peeled bark such as roots. By doing this, the amount of photosynthates distributed to the fruit is increased. The peeled bark recovers naturally in a few weeks and photosynthates can be sent to the roots once again.

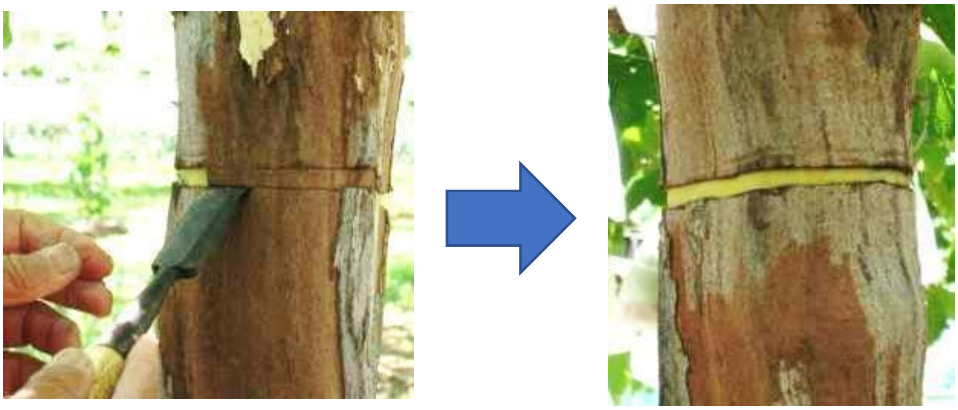

Fig. 8. Girdling of a trunk of grape.

However, girdling inhibits rooting (Yamane and Shibayama, 2006) and decreases grapevine vitality (Kugimiya *et al*., 2011), and the process needs to be carried out more than one month before harvest. It is possible to minimize the adverse effects by carrying out the procedure only in the years when the skin coloration at harvest is estimated to be poor. Thus, we developed a method to predict the skin color of grape berries at harvest (Sugiura *et al*., 2018).

The main cause of death of flower buds of Japanese pear is cold damage. The application of fertilizer and compost in fall or winter reduced freezing tolerance. Changing the timing of fertilizer application from fall or winter to spring reduced bud death significantly (Sakamoto *et al*., 2017).

Cultivar selection and breeding (stage 2)

As fruit trees are replanted only once in about 30 years, it is difficult to introduce a new cultivar to a commercial fruit orchard; however, adaptation measures using production technology (stage 1) requires extra cost and labor every year. Therefore, some cultivars have already been developed to be more tolerant to warming. Bud mutations of the major apple cultivars "Fuji" and "Tsugaru" have been selected, which color more readily than the parent cultivars.

New cultivars adapted to warming have recently been developed, such as superior-colored cultivars of apple ("Kinshu" and "Beniminori") and grape ("Queen Nina" and "Gross Krone"), a yellow cultivar of apple ("Morinokagayaki") and grape ("Shine-muscat") without coloring problems, and a Japanese pear cultivar resistant to dead flower buds ("Rinka").

Japanese peach cultivars require long periods of exposure to low temperature for completion of endodormancy to achieve flower bud break.

However, endodormancy completion of some foreign cultivars needs only a short chilling period. As these cultivars do not have such good quality as the Japanese cultivars, a peach cultivar combining a low chilling requirement with high fruit quality ("Sakuhime"; Sawamura *et al.*, 2017) has been developed by crossing the foreign cultivar with Japanese cultivars.

New citrus cultivars, such as "Siranui," "Setoka," "Harehime," and "Mihaya," have good flavor and can also be peeled by hand like a satsuma mandarin. These have been developed by cross-breeding satsuma mandarin with oranges that are resistant to peel puffing and are better suited to higher temperatures.

Movement of production areas (stage 3)

Since fruit trees are vulnerable to the effects of climate change, there is a possibility that the areas suitable for fruit cultivation will change because of global warming. For the stage 3, the movement of production areas, we have created predictive maps showing future areas suitable for several fruit tree crops, for producers and local governments.

For example, most apple trees are currently cultivated in the northern part of the temperate zone in Japan, since they need to be planted in cold climates. The temperature ranges assumed to be appropriate for the cultivation of apple are 6–14°C in terms of annual mean temperatures. A database (Yokozawa *et al.*, 2003) was used to simulate possible changes in favorable regions for the cultivation of apple, with approximately 10 × 10 km resolution.

The favorable regions to cultivate apples were predicted to gradually move northwards. Many parts of the current apple producing districts in Japan will possibly be unfavorable by the 2060s (Fig. 9; Sugiura and Yokozawa, 2004). Maps of future suitable areas were also developed for satsuma mandarins (Sugiura, 2016), which are the most common fruit trees in Japan, and for tankans (Sugiura *et al.*, 2014), which are subtropical citrus fruits.

Satsuma mandarin is currently suitable for growing in the area along the Pacific Ocean side of eastern Japan and western Japan, but predicted climate change over the next 50 years means that this may move to the Japan Sea side of Honshu and the coastal area of south Tohoku. Coastal areas of the current satsuma mandarin–producing regions in Japan will then be suitable for tankan production by 2050 (Fig. 10).

For these reasons, planting of new fruit trees is progressing slowly. Peaches are being planted instead of apple in the northern part of Tohoku, while growers have succeeded in cultivating the subtropical fruit blood orange in place of satsuma mandarin in Ehime Prefecture. Fields of citrus fruits, Japanese persimmons, and grapes, which are often cultivated on sloping land, are being relocated to higher altitudes in some places.

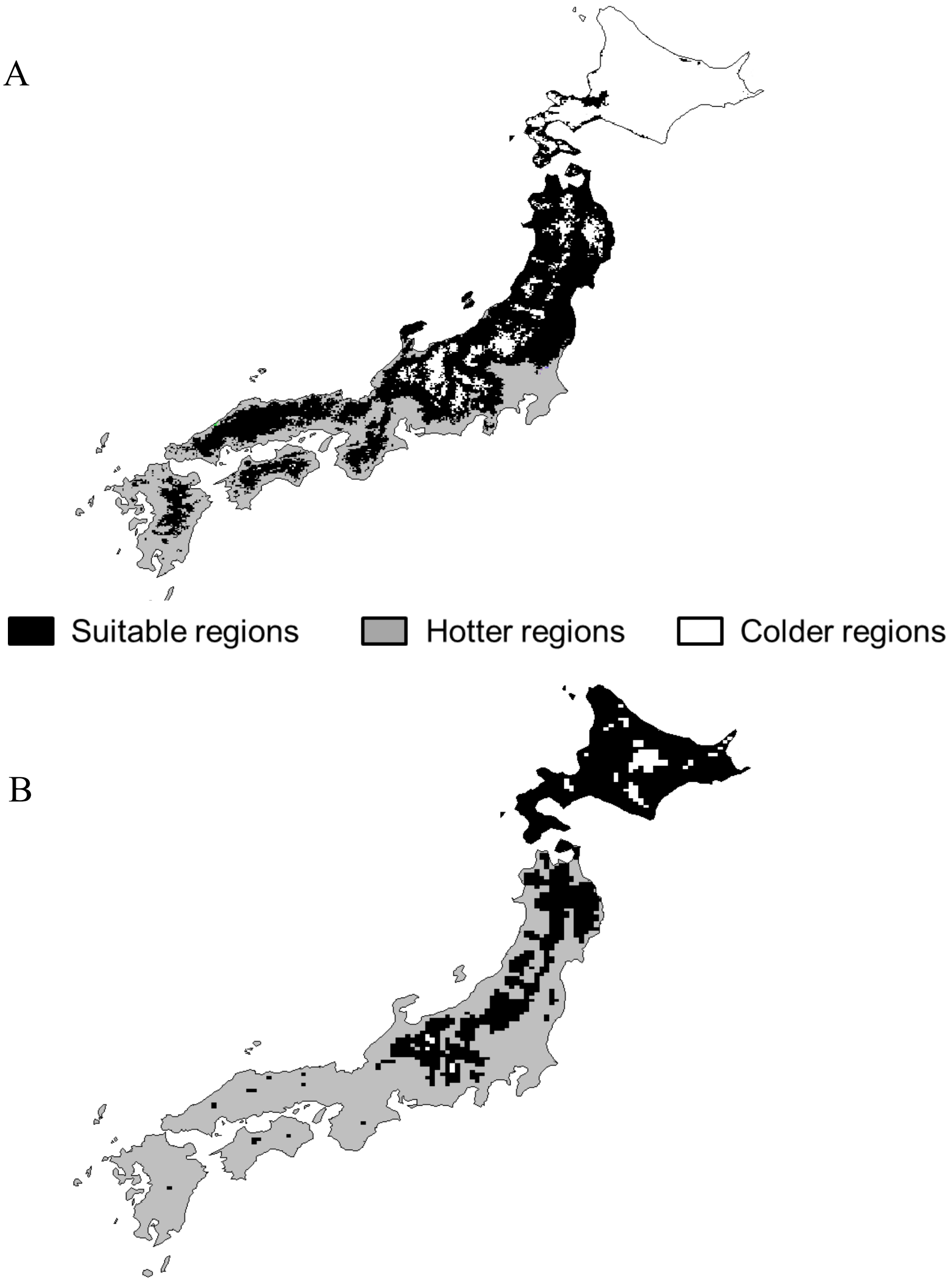

Fig. 9. Predicted change in the spatial distribution of regions suitable for apple production under (A) current climate (1971–2000) and (B) predicted climate in the 2060s.

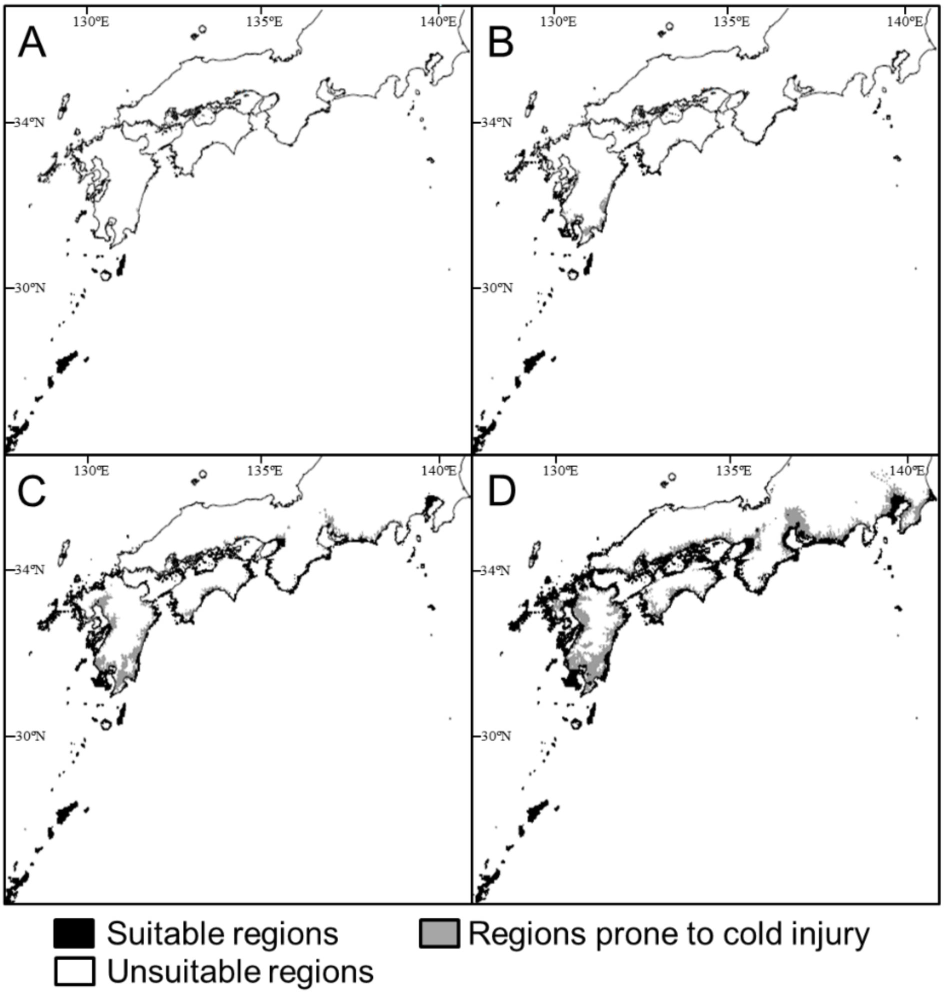

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Fig. 10. Predicted change in the spatial distribution of regions suitable for tankan production under (A) current climate (1981–2000) and (B–D) predicted climate in (B) 2011–2030, (C) 2031–2050, and (D) 2051–2070.

CONCLUSION

The impact of climate change on fruit trees has already become obvious. We have developed many adaptation measures, but it is considered that climate change will progress even further. Therefore, the development of adaptation measures needs to continue into the future.

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