Varietal Assessment of Threshold Air Temperatures for Cold Damage in Loquat Fruit

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Shift in locations suitable for loquat [Eriobotrya japonica (Thunb.) Lindl.] due to global warming leads to a high requirement for accurate assessment of suitable locations. This study aimed to develop a technique for using past winter air temperatures to judge whether an area is suitable for loquat production. The relationship between air temperatures and cold damage levels observed in orchards of four main production areas (Chiba, Kagawa, Nagasaki, and Kagoshima prefectures) for some years were analyzed. The survival rates of young fruit of each variety were positively correlated with the annual minimum air temperature. Threshold air temperatures for cold damage (the air temperature at which the survival rate decreased to 80%) of six varieties (‘Tanaka’, ‘Mogi’, ‘Natsutayori’, ‘Nagasakiwase’, ‘Harutayori’, and ‘Biwa Nagasaki No. 21’) were acquired by using statistically significant linear regressions. ‘Tanaka’ had excellent cold hardiness, with the lowest threshold air temperature, whereas ‘Nagasakiwase’ and ‘Harutayori’ tolerated the cold less well, with higher threshold air temperatures. Locations suitable for production of ‘Tanaka’ and ‘Nagasakiwase’ were judged based on the upper limit of the threshold air temperature for cold damage. The current production areas agreed with the locations judged to be suitable for the production of each variety. These results suggest that the threshold air temperatures for cold damage obtained in the present study provide a valid assessment of suitable current and future locations for both varieties.

Key Words: annual minimum air temperature, climate change, cold death, cold hardiness, suitable locations.

Introduction

Loquat [Eriobotrya japonica (Thunb.) Lindl.] flowers in the fall or winter, and produces young fruit in mid-winter; therefore, cold damage is a severe climatic hazard for loquat trees. Since the level of cold damage is one of the most important factors determining loquat yield (Kihara et al., 1982), the susceptibility to cold damage limits the locations suitable for establishing loquat orchards (Matsumoto et al., 1990; Muramatsu, 1971; Yoshimura et al., 1983). Thus, assessment of the frequency of cold damage based on past air temperatures in the area is a prerequisite for new plantings of loquat.

‘Obusa’, cold-hardy variety (Iwasaki, 1967), is the main variety in eastern Japan, but is not cultivated in western and southern Japan (Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2015a), where the climate is warmer. This implies that the cold hardiness affects also selection of variety by loquat producers. It is important that the threshold air temperatures for cold damage be identified for each variety to
support this selection.

Previous studies of loquat cold hardiness have involved either surveys of cold damage in specific areas in certain years (Kihara et al., 1982; Matsumoto et al., 1990; Nakai and Morioka, 1978, 1979; Yoshimura et al., 1983; Zhang et al., 2007), or examinations of the cold death rate of young fruit by using freezers (Miki and Nagasawa, 1935; Nagasaki Prefecture, 1978).

Since cold hardiness varies according to the developmental stage of the fruit (Nakai and Morioka, 1978; Polat and Caliskan, 2011), the level of cold damage changes depending on the timing of cooling, even in the same tree. Other factors that affect the level of cold damage in the field, such as tree height (Yoshimura et al., 1983), are also known. Therefore, an air temperature that causes cold damage cannot be accurately determined by observations in a single area in a single year, and the level of cold damage in other areas cannot be estimated by using those results.

On the other hand, although the relationship between fruit temperature and the cold death rate can be evaluated by cooling experiments with freezers, it is difficult to directly determine the threshold air temperatures that cause cold damage on account of the large gap between the air temperature and the fruit temperature in an orchard (Nakai and Morioka, 1979).

The Japan Meteorological Agency (2014) reports that the mean air temperature in Japan is rising at a rate of 1.14°C per 100 years and that global warming will continue. Areas suitable for evergreen fruit trees are expected to expand northward (Sugiura and Yokozawa, 2004; Sugiura et al., 2014). This shift in the locations suitable for loquat due to global warming will create a strong need to accurately assess suitable locations.

The objective of the present study was to develop a technique based on using past winter air temperatures to judge whether an area is suitable for growing loquat. For this purpose, we clarified the relationship between air temperature and the level of cold damage to several loquat varieties by means of a comprehensive analysis of the cold damage levels that actually occurred in orchards in a number of major production areas. Moreover, since levels of cold damage change according to certain other factors, even if the air temperature is the same, a safer method for determining suitable locations was developed based on estimating the range of variation in the levels of cold damage. The validity of these threshold air temperatures for predicting cold damage to two representative varieties (‘Tanaka’ and ‘Nagasakiwase’) was examined by comparisons between the actual production areas and locations judged to be suitable based on the threshold air temperature.

### Materials and Methods

#### Plant materials and experimental locations

The level of cold damage in young loquat fruit in several major production areas was observed from 2008 to 2014 in experimental loquat orchards (Table 1) located in Tateyama, Chiba Prefecture (35.0°N, 139.9°E); Sakaide, Kagawa Prefecture (34.3°N, 133.9°E); Omura, Nagasaki Prefecture (32.9°N, 130.0°E); and Tarumizu, Kagoshima Prefecture (31.5°N, 130.7°E). Six varieties (‘Tanaka’, ‘Mogi’, ‘Natsutayori’, ‘Nagasakiwase’, ‘Harutayori’, and ‘Biwa Nagasaki No. 21’) were used in this study. ‘Biwa Nagasaki No. 21’ is a line selected from a cross of ‘Nagasakiwase’ × ‘Ryoho’. Table 1 summarizes the observation years and the average tree ages in all orchards.

#### Observation of cold damage

In total, more than 30 young fruits from each variety were picked at random parts throughout the trees in the middle of March, a time after which air temperatures rarely dropped to levels that cause cold damage. Young fruit in which seeds had changed from green to black were judged as having succumbed to cold death (Nakai and Morioka, 1978). The survival rates were calculated as the proportion of the fruits that were not dead as a result of cold damage.

Low levels of cold damage do not decrease fruit yield, because farmers usually thin fruits after the period in which cold damage occurs and only a few fruits are allowed to set in each fruit cluster (Nakai and Morioka, 1978). Therefore, in the present study, we

### Table 1. Prefectures and years in which each variety was examined for cold damage.

| Variety           | Prefecture       | Observation years | Average tree age (years) |
|-------------------|------------------|-------------------|--------------------------|
| ‘Tanaka’          | Chiba            | 2008–2014         | 7.3                      |
| ‘Mogi’            | Chiba            | 2008–2014         | 8.6                      |
| ‘Natsutayori’     | Chiba            | 2009–2014         | 10.5                     |
| ‘Nagasakiwase’    | Chiba            | 2008–2014         | 8.4                      |
| ‘Harutayori’      | Chiba            | 2008–2014         | 9.9                      |
| ‘Biwa Nagasaki No. 21’ | Chiba            | 2008–2014         | 7.5                      |

* No observation.

* Years when the annual minimum air temperature was above –2°C are in italics.

* The average tree age for all orchards and years of observation.
Climate data

For the daily minimum air temperatures in each experimental orchard, we used the daily minimum air temperatures in the “AMeDAS mesh data” (Seino, 1993), a mesh climate dataset (with grid cells 45” in longitude × 30” in latitude; i.e., 1 km square) estimated using statistics from meteorological observation stations across Japan from 1978. The minimum value of the daily minimum air temperatures from early January to early March was defined as the annual minimum air temperature.

Judgment of locations suitable for loquat production

Locations suitable for the ‘Tanaka’ and ‘Nagasakiwase’ loquat varieties were judged from the potential frequency of cold damage. MAFF (2015b) defines locations suitable for citrus as those locations where cold damage occurs no more than 1 year per decade. In a similar manner, we judged locations potentially suitable for loquat to be those locations where the annual minimum air temperature was less than the threshold air temperature for cold damage in no more than 2 years out of the 20 years from 1991 to 2010. The daily minimum air temperatures from 1991 to 2010 in the “AMeDAS mesh data” were used to judge suitable locations.

Results and Discussion

Threshold air temperature for cold damage

The survival rate of each variety was significantly positively correlated with the annual minimum air temperature (Fig. 1 and Table 2) in years when the annual minimum air temperature was −2°C or less (Table 1). Since previous investigations using freezers have also shown that a lower survival rate is caused by lower fruit temperature (Miki and Nagasawa, 1935; Nagasaki Prefecture, 1978), the annual minimum air temperature plays an important role in determining the level of cold damage.

The threshold air temperature for cold damage (the air temperature at which the survival rate decreased to 80%) was acquired by linear regression of these relationships (Table 2). ‘Tanaka’ had excellent cold hardness, with the lowest threshold air temperature, whereas ‘Nagasakiwase’ and ‘Harutayori’ tolerated the cold less well, with higher threshold air temperatures. Previous studies suggested that the cold tolerance of ‘Tanaka’ was higher than that of ‘Mogi’ (Muramatsu, 1971) and that the cold tolerance of ‘Nagasakiwase’ was lower than that of ‘Mogi’ (Yoshimura et al., 1983). Our results support the conclusions of those previous studies.

The changes in cold hardness that occur between fruit developmental stages (Nakai and Morioka, 1978; Polat and Caliskan, 2011) imply that the survival rate changes depending on the time when the air temperature drops to the annual minimum air temperature. The survival rate is also affected by the cooling duration (Nagasaki Prefecture, 1978), wind speed (Nakai and Morioka, 1979), fruit position in a tree (Nakai and Morioka, 1978), and tree height (Yoshimura et al., 1983). These factors are likely to be responsible for the residual differences between the regression line and the observed values (Fig. 1).

The range of variation in the air temperature at which the survival rate decreases to 80% was estimated from the 95% confidence interval for the population regression line (Table 2). For instance, for ‘Mogi’, the threshold air temperature for cold damage ranged from −4.4°C to −7.3°C. Therefore, the value of −4.4°C, which represents the upper limit of the threshold air temperature, represents a safer target for determining the suitability of a location for this cultivar than −5.2°C, the threshold air temperature calculated directly from the regression formula.

The survival rate never exceeds 100%, even when the annual minimum air temperature is high enough, and the survival rate never falls below 0%, even when the annual minimum air temperature is significantly low. This suggests that the relationship between the annual minimum air temperature and the survival rate forms a logistic curve rather than a straight line if the relationship had been investigated over a wider temperature range. In the present study, no data for survival rate was obtained for annual minimum air temperatures under −6°C, and the survival rate data was excluded when the annual minimum air temperature was above −2°C. This narrow range of annual minimum air temperatures may allow accurate approximation of the relationship between temperature and damage using a straight line.

Slopes of the regression lines for ‘Tanaka’ and ‘Mogi’ were about 5%/°C, but those of other varieties were more than 17%/°C (Table 2). The survival rates measured for ‘Tanaka’ and ‘Mogi’ were mostly greater than 80%, so the slopes for ‘Tanaka’ and ‘Mogi’ were low. If we had been able to include survival rate data for lower annual minimum air temperatures, then the values of the slopes would likely have been higher for a linear regression. Additional work is required to determine the complete relationship between annual minimum air temperature and survival rate.

Assessment of suitable locations

Locations suitable for production of the representative varieties ‘Tanaka’ and ‘Nagasakiwase’ were judged based on the upper limit of threshold air temperature for cold damage of each variety (‘Tanaka’, −5.0°C; ‘Nagasakiwase’, −2.2°C) (Fig. 2). The most northerly defined the air temperature that causes cold damage to be that at which the survival rate is less than 80%, and defined the air temperature at which the survival rate decreased to 80% to be the threshold air temperature for cold damage.
Fig. 1. Relationship between the survival rate of each variety and the annual minimum air temperature. Lines represent statistically significant linear regressions (see Table 2).

Table 2. Correlation coefficients, linear regression parameters, and threshold air temperatures for cold damage to loquat.

| Variety        | Survival rate (%) | Annual minimum air temperature (°C) | Threshold air temperature (°C) | Upper limit (°C) | Lower limit (°C) |
|----------------|-------------------|-------------------------------------|--------------------------------|------------------|------------------|
| 'Tanaka'       | 8                 | 0.802                               | -6.0                           | -5.0             | -12.2            |
| 'Mogi'         | 17                | 0.671                               | -5.2                           | -4.4             | -7.3             |
| 'Natsutayori'  | 12                | 0.868                               | -3.4                           | -2.8             | -3.8             |
| 'Nagasakiwase' | 19                | 0.709                               | -3.0                           | -2.2             | -3.4             |
| 'Harutayori'   | 20                | 0.660                               | -2.8                           | -1.5             | -3.4             |
| 'Biwa Nagasaki No. 21' | 15          | 0.885                               | -3.3                           | -2.8             | -3.6             |

* Number of observation data, excluding years when the annual minimum air temperature was above -2°C.
* Pearson’s correlation coefficient between survival rate and annual minimum air temperature.
* P value of r.
* Regression parameters (y=ax+b, where y is the survival rate, x is the annual minimum air temperature, a is the slope, and b is the intercept).
* Threshold air temperature for cold damage (the air temperature at which the survival rate decreases to 80%) calculated from the regression formula.
* The upper and lower limits of the threshold air temperature for cold damage were estimated from the 95% confidence interval for the population regression line.
area currently used for production of loquat is the southern end of the Boso Peninsula in Chiba Prefecture (MAFF, 2015c), where ‘Tanaka’ loquat is mainly produced (MAFF, 2015a). Our assessment (Fig. 2B) also showed that suitable locations for ‘Nagasakiwase’ were distributed mainly in the remote islands around Kyushu and in a few places on Kyushu Island itself, other than coastal areas on the southern end of Kyushu.

The actual production areas were consistent with the locations predicted to be suitable. Although the validity of the threshold air temperatures for the other varieties cannot be tested due to a lack of precise information on the actual production areas, the results for these two representative varieties suggest that the threshold air temperatures for cold damage obtained in the present study will be useful for predicting suitable locations.

Intergovernmental Panel on Climate Change (IPCC) (2013) estimated that the global average surface air temperature will rise by 1.0 to 3.7°C during the 21st century, and that the frequency of extremely cold nights will decrease over most land areas. This implies that the frequency of cold damage should decrease and that locations suitable for cold-sensitive crops such as loquat will expand. The threshold air temperatures for cold damage obtained in the present study will enable prediction of the northward shift of the northern limit for the production of loquat.

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