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The Horticulture Journal *Preview*
doi: 10.2503/hortj.OKD-044

The Japanese Society for
Horticultural Science
http://www.jshs.jp/

Selection of Prune (*Prunus domestica* L.) Cultivars Suitable for the East Asian Temperate Monsoon Climate: Ripening Characteristics and Fruit Qualities of Certain Prunes in a Warm Southwest Region of Japan

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Prune trees (*Prunus domestica* L.) are optimally suited to dry climates, and a major production area for prune trees is California, which has little rainfall. The East Asian temperate monsoon zone, where summer is hot and rainfall is relatively abundant, is not well suited for cultivating prune trees. The purpose of this study was to investigate prune cultivars that are ideal for this temperate monsoon zone to expand the possibility of production. We evaluated the performance of 8 prune cultivars, 'Puchull', 'Purple Ais', 'Blue Tan', 'Edwards', 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling', by harvesting fruits from August to October to identify optimal cultivars in Izumo, western Japan, as a model area in the temperate climate monsoon zone. Results showed that the flowering period of prune trees was from late March to mid-April, and average temperature in March influenced whether flowering time would occur early or late. The flowering period varied by year. Therefore, companion planting with other cultivars that have overlapping flowering periods is necessary for self-incompatible cultivars. To avoid spring frost damage during the flowering period, protection from frost was necessary. Additionally, to avoid fruit cracking, cultivating prune trees under rain shelter conditions was also necessary. With these management approaches, two mid-ripening types, 'Stanley' and 'Valor', and two late-ripening types, 'President' and 'Marjorie's Seedling', yielded over 1000 kg/10 a/canopy area and produced high-quality fruit with over 20 soluble solids content (SSC)/titratable acid (TA). However, three early-ripening types, 'Puchull', 'Purple Ais', and 'Blue Tan', and the mid-ripening 'Edwards', showed relatively low yields and produced fruit with low SSC/TA. Moreover, flesh darkening before harvest was observed as a result of high-temperature injury in these cultivars, and skin color and fruit taste were not good enough before flesh darkening; thus, these four cultivars were not suitable for table use. In summary, we consider mid- to late-ripening cultivars suitable for table use in Izumo. Our findings also indicate the possibility that these prune fruit cultivation methods could be used in other parts of the East Asian temperate monsoon and humid temperate climate zone.

Key Words: flowering time, high-temperature injury, soluble solids content/titratable acid ratio, table use, yield.

Introduction

The European plum (*Prunus domestica* L.), also called a prune, belongs to the subgenus *Prunus* in genus *Prunus* (Rosaceae). Although the origin of the European plum, a major prune species, remains unclear (Hartmann and Neumüller, 2009), prunes probably arose from the Caucasus region which is surrounded by the Caspian and Black Seas. Prune fruit contains various minerals, vitamins, and functional components such as polyphenols, and is noted as a nutritional food (Kim et al., 2003). The prune fruit is thought to have an effect on intestinal regulation and reduce constipation because sorbitol is abundantly contained within its sugar (Cordova and Watson, 2011).

Prune trees are best suited for cool and dry climates,

Received; August 5, 2016. Accepted; November 16, 2016.
First Published Online in J-STAGE on January 31, 2017.
Part of this study was presented at the 2013 Autumn Meeting of the Japanese Society for Horticultural Science.
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and so have been mainly cultivated in western Asia, Europe, and North America, where there is less rainfall in the summer, and the fruit is generally dried. From 2014 to 2015, dried prune production worldwide was about 250000 t (International Prune Association (IPA), 2015). The United States of America (USA) produced 120000 t of prunes, representing about 48% of the world's production, followed by Chile, France, and Serbia. The current European plum breeding program, however, seems to favor using fresh fruit (Neumüller, 2011; Okie and Ramming, 1999).

Most of the Japanese growing regions are in the East Asian temperate monsoon climate zone. In Japan, prune cultivation began around the 1860s to 1880s, and prunes are primarily grown in the eastern region due to the relatively cool climate. The total cultivated area and production of Japanese prunes in 2013 were 491 ha and 2733 t, respectively (Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2013). Since 1965, the major prune production region has been Nagano Prefecture, having 54.8% of the Japanese prune cultivation land area and 67.7% of national prune production. In Japan, prunes are mainly cultivated as fresh fruit because the harvesting season is very rainy, while approximately 10000 to 20000 t of dried prunes are imported (California Dried Plum Board/California Prune Board, 2016).

According to the climate classification of Köppen-Geiger (Peel et al., 2007), most western Japanese regions, including Shimane Prefecture, lie in a humid temperate climate zone with relatively abundant rainfall and hot summers. However, Nagano Prefecture, the major prune production region, is in a subarctic humid climate zone with relatively hot summers. Prune skin cracking is caused by excessive rainfall in the late immature to mature stages of the fruit, as also occurs in the cultivation of sweet cherries (Imagawa, 2000; Measham et al., 2014; Sekse, 1995). During the frost season from March to April in western Japan, frost damage may occur in many fruit trees. Therefore, prune cultivation is generally not well-suited to western Japan, including Shimane Prefecture. Fruit cracking in prunes has been prevented by covering the trees with plastic film before harvesting or throughout the growing season in Japan. This method enables production and shipment of fully tree-ripened prune fruits (Kurahashi, 1998). To increase sales profits by intensive farming, fresh, high-quality prune fruits and high unit prices are desired. In addition, certain prune tree cultivars are self-incompatible (Hartmann and Neumüller, 2009); such cultivars need adequate pollinizers that have approximately the same flowering timing, and require pollination by hand or insects.

In dried prune production regions, such as California or Chile, the 'd'Agen' cultivar is primarily cultivated (IPA, 2015). In fresh prune production regions, including some European countries and parts of North America, the 'Stanley', 'President', and 'Bluefre' are often cultivated (Ramming and Cociu, 1991). In Europe, where breeding of prune cultivars has been actively conducted, various cultivars are grown including domestic breed, imported, and traditionally raised cultivars (Blažek et al., 2004; Bozhkova, 2014; Okie and Ramming, 1999; Rakićević et al., 2008; Šebek, 2013). In Japan, growing areas for 26 prune cultivars have been recorded, most of which are imported (MAFF, 2013). Among them, the most common is 'Sun Prune', comprising 26.1% of production, followed by 'Sugar' and 'Stanley' (12.1% and 9.4%, respectively), all three of which are self-compatible cultivars.

Functional components and anti-oxidant effect of prunes have recently been reported (Kimura et al., 2008; Slimestad et al., 2009; Thurow and Lee, 2012), along with an increase in demand for fresh prune fruits (Okie and Ramming, 1999). Production amounts of high quality fresh stone fruits, including prune fruit, is limited due to the difficulty in obtaining the necessary manpower during the optimum harvesting and packing time. Also, these fruits have a relatively short postharvest life (Crisosto et al., 1995). These conditions point to a need for the expansion of prune production regions to meet the demand of quickly delivered fresh fruits. Therefore, in the present study, we investigated the growth and fruit quality of 8 prune cultivars, harvesting fruits from August to October (late summer to autumn), in search of prune cultivars suited to an East Asian monsoon climate or to a mild humid climate, in order to expand the potential production into areas other than those characterized by dry or Mediterranean climates.

Materials and Methods

Cultivars and orchard

In this study, we investigated the performance of 8 prune cultivars: 'Puchull', 'Purple Ais', 'Blue Tan', 'Edwards', 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling'. 'Stanley', was released in USA, is grown around the world (Okie and Ramming, 1999) and was selected as standard cultivar. The harvesting periods of the other 7 cultivars were different from that of 'Stanley' in Nagano Prefecture, the major prune production area, and the nursery stocks of these cultivars could be purchased in Japan. 'Edwards', 'Valor', 'President', and 'Marjorie's Seedling' were introduced from England and Canada, and the origin of the 3 other cultivars was unknown. Between 2 and 14 trees of each cultivar were grown under a rain shelter, trained on a flat trellis, and planted in line at a spacing of 6 m × 3 m in a field of 10 a at Shimane Agricultural Technology Center, Japan. The investigation was conducted from 2009 to 2011, with 4-, 5-, or 11-year-old trees ('Puchull' and 'Purple Ais'; 'Blue Tan', 'Edwards', and 'Marjorie's Seedling'; and 'Stanley', 'Valor', and 'President', respectively) in the first season and all cultivars were grafted onto Myrobaran root stocks (purchased from a nursery stock trader; Nippon ryokusan, Matsumoto, Japan). Then, 2 trees of 'Puchull' and 'Purple Ais' and 3 trees of other cultivars were selected and used for investigation, and 3 healthy growing trees were not affected by the edge effect. Self-incompatible cultivars ('Puchull', 'Purple Ais', 'Blue Tan', 'Edwards', 'Valor', and 'President') were artificially pollinated. Self-compatible cultivars ('Stanley' and 'Marjorie's Seedling') were not artificially managed to allow natural pollination. Irrigation, fertilization, and pest management were done following standard protocols. Manual fruit thinning was performed 30, 60, and 90 days after full bloom (DAFB) to prevent the fruits from touching each other at harvest. Fertilizer was applied annually to mature trees at rates of N: 16, P_2O_5: 10, K_2O: 11.6, CaO: 18.3, and MgO: 5 kg/10 a.

Phenology and fruit quality

Investigations of growth and fruit quality characteristics were conducted according to the established investigation method of the National Agriculture and Food Organization Institute of Fruit Tree Science (2007). For phenology evaluation, both flowering and harvest times were recorded. Flowering time was recorded as follows: onset of bloom was defined when 20% of flowers bloomed, full bloom was defined when 80% of flowers bloomed, and end of bloom was defined when 95% of the flowers bloomed or corollas started to fall off. The harvesting date was determined when fruit became relatively soft to the touch. The tree crown area of each tree was measured after harvest.

To determine fruit traits, we harvested 3–6 mature fruits from each tree in 2009 and 10–20 mature fruits from each tree in 2010 and 2011. The following items were measured immediately after harvesting: fruit weight, fruit shape, skin and flesh colors, fruit and flesh firmness, soluble solids content (SSC), fruit juice acidity, and fruit stone freeness. In 2011, waxy bloom thickness, titratable acidity (TA), and juice recovery rate were measured from 10 fruits per cultivar. After removal of the waxy bloom with a cloth, skin ground color was measured on the two equatorial portions of each fruit using a colorimeter (Color Reader CR-10; Minolta, Osaka, Japan). Based on the colorimeter measurement, skin ground color was expressed as the L*, a*, b*, and h* values. Fruit firmness, expressed in kg, was measured by penetrating the skin and flesh using a penetrometer (Fruit Hardness Tester KM-1; Fujiwara Scientific, Tokyo, Japan) fitted with a 12-mm corn-type plunger. To measure flesh color and firmness, approximately 2-cm-thick axial slices were cut out using a sharp knife. Flesh color and firmness on the sliced surface were measured using a colorimeter and penetrometer, respectively. SSC was measured on the axial slice of each fruit with a refractometer (N-1E; Atago, Tokyo, Japan). The skin and flesh color, fruit and flesh firmness and SSC were measured on the right and left sides of each fruit. Stone freeness was classified into clingstone, semi-clingstone, semi-freestone, and freestone. Juice was extracted from half to one-third of each fruit using an extractor (Super Extractor; Atago), filtrated through gauze, and squeezed out by hand. Juice recovery was calculated by dividing the volume of juice by the weight of the fruit after squeezing and then multiplying that value by 100. TA was determined by titration with 0.1 N NaOH to a phenolphthalein endpoint and conversion to malic acid. To evaluate waxy bloom thickness, we defined 4 stages of waxy bloom thickness using 'Stanley' based on the visually observed amount of manually removed waxy bloom (1: very small amount, 2: small amount, 3: medium amount, 4: large amount). Then, we calculated a value by subtracting the L* value of the skin color after waxy bloom removal from that before removal. A significant correlation was noted between visual observation of waxy bloom (X) and the subtracted L* values (Y), ($Y = 3.305X + 2.3667$, $R^2 = 0.7905$, data not shown). Therefore, the subtracted L* values of the fruit skin were regarded as indices for waxy bloom thickness. To investigate the time course of skin ground color and flesh color, 3 to 5 fruits were collected from each tree every 7 days in 2010 and 2011. Fruit collection began approximately 80 DAFB in 2010 and 50 DAFB in 2011. Fruit and flesh firmness, skin and flesh color, and SSC were assessed with a penetrometer, colorimeter, and refractometer, respectively. Juice acidity was assessed using a simplified pH meter (B-211; HORIBA, Tokyo, Japan).

Statistical analysis

Data obtained in this study (yield and fruit quality) were subjected to analysis of variance (ANOVA). Juice recovery of fruit weight was arcsine root-square transformed prior to ANOVA. Mean comparisons were performed using the Tukey–Kramer multiple range test to examine differences ($P < 0.05$). The statistical analysis of collected data was performed using statistical software (Ekuseru–toukei 2015; Social Survey Research Information, Tokyo, Japan).

Results

Climate of the prune production area

According to the Japan Meteorological Agency database, the average temperature during the growing season in major prune production areas worldwide is known to range from 15.0 to 19.3°C, although there is variation among production areas (Table 1). Annual and growing season rainfall are under 712 mm and 491 mm, respectively; thus, the climates of major prune production areas are considered relatively dry. Saku, Nagano Prefecture, is a major prune production area in Japan with an average annual rainfall of 961 mm, which indicates relatively abundant rain compared with other locations worldwide. In Izumo, Shimane Prefecture, which was selected as a model area located in a western

Table 1. Average temperature and rainfall in prune production areas of Japan and other countries.[z]

		Japan		USA	Chile	France	Serbia
		(Izumo)	(Saku)	(Sacrament)	(Valparaiso)	(Agen)	(Beograd)
Temperature (°C)	Annual	14.6	10.6	15.9	14.0	13.4	12.5
	Growing season	18.4	17.1	19.3	15.0	16.6	17.0
	Winter season	5.5	−0.6	8.4	11.7	6.2	2.4
Rainfall (mm)	Annual	1685	961	459	373	712	691
	Growing season	1129	788	147	64	482	491
	Winter season	342	77	242	254	167	144

[z] All data indicate mean values from 1981 to 2010.

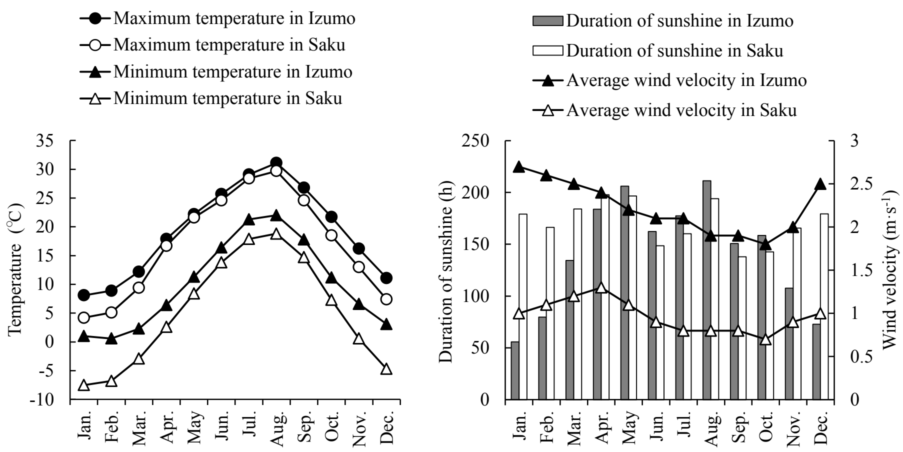

Fig. 1. Maximum and minimum temperature, duration of sunshine, and average wind velocity of Izumo city and Saku city for each month. Temperature and wind velocity data indicate mean values from 1981 to 2010, and duration of sunshine indicate mean values from 1987 to 2010.

part of Japan, annual rainfall is 1685 mm, which is typical for temperate monsoon zone and far greater than that of Saku. There are no significant differences between Izumo and Saku regarding maximum temperature and duration of sunshine during the growth period of prune trees (Fig. 1). However, during the ripening season of prune fruit, from July to October, minimum temperatures for Saku are low with over a 10°C difference between night and day temperatures. Further, Izumo tends to be affected by seasonal winds, averaging wind speeds greater than 2 m·s^{-1} throughout the year.

Flowering and harvesting times, and fruit characteristics

Flowering and harvesting dates from 2009 to 2011 are shown in Figure 2. The flowering period of all prune cultivars investigated was from late March to mid-April during the three years; it was slightly earlier and longer in 2009 compared with that in 2010 and 2011, and the highest average temperature was recorded in March 2009. The lowest average temperature among the three years was recorded in March 2011; flowering time was delayed and cultivar differences in flowering time were not clear. Comparative differences in flowering time among cultivars were similar across the three years, excepting for 'Purple Ais'. The harvest time for each cultivar was relatively stable across the three years, except for 'Blue Tan'. 'Puchull' and 'Purple Ais' matured in mid- to late August (early maturation type); 'Edwards', 'Stanley', and 'Valor' matured in early September to early October (middle maturation type); and 'President' and 'Marjorie's Seedling' matured in mid- to late October (late maturation type).

Fruit yields and quality

The fruit yield per canopy area exceeded 1000 kg/10 a for 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling' (Table 2). In particular, 'Valor' showed the highest yield, with over 1800 kg/10 a/canopy area throughout the three years. However, 'Puchull', 'Purple Ais', and 'Blue Tan' had markedly low yields of less than 775 kg/10 a.

'Purple Ais', 'Edwards', and 'President' had the largest fruits (about 100 g/fruit), whereas 'Puchull' and 'Stanley' had the smallest fruits (about 55 g/fruit) (Table 3). Fruit shape varied including round, short-oval, fusiform, and elliptical, although a short-oval shape was the most common. Prunes are classified according to the adherence of the flesh to the stone: freestone, semi-freestone, semi-clingstone, and clingstone. 'Puchull', 'Stanley', 'Valor', and 'President' are cate-

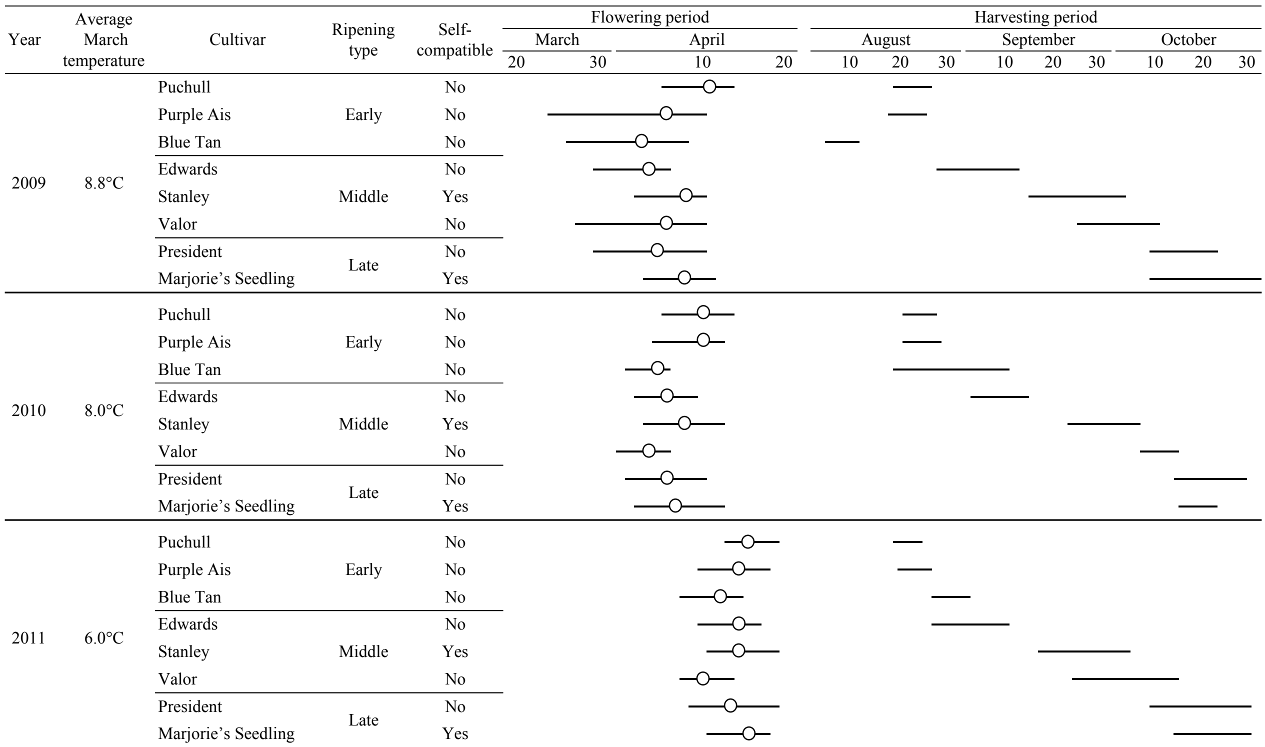

Fig. 2. Flowering and harvesting periods of prune trees grown in Shimane Prefecture, Japan from 2009 to 2011. Horizontal lines indicate flowering or harvesting period and ○ indicates full flowering time.

Table 2. Fruit yield comparisons of prune cultivars grown in Shimane Prefecture, Japan from 2009 to 2011.

Cultivar	Fruit yield[z] (kg/10 a)		
	2009	2010	2011
Puchull	337.6 b[y]	159.9 c	375.0 c
Purple Ais	284.5 b	307.7 c	775.1 bc
Blue Tan	456.1 b	661.2 bc	441.8 c
Edwards	469.8 b	744.2 bc	1181.8 abc
Stanley	1376.7 a	1639.1 a	1832.0 ab
Valor	1882.5 a	1979.6 a	1907.5 a
President	1382.1 a	1092.4 bc	1278.8 abc
Marjorie's Seedling	1704.3 a	1292.9 ab	1673.1 ab

[z] Fruit yield per canopy area that used a flat trellis.
[y] Different lowercase letters indicate significant differences based on the Tukey–Kramer multiple range test ($P<0.05$).

gorized as freestone; 'Purple Ais' and 'Marjorie's Seedling' as semi-freestone; and 'Blue Tan' and 'Edwards' as semi-clingstone. The highest fruit firmness, measured using the whole fruit with skin, was more than 0.70 kg in 'Stanley' and 'President'; the lowest was 0.56 kg in 'Puchull'. 'Stanley' had the highest flesh firmness (0.53 kg), followed by 'President', 'Blue Tan', and 'Marjorie's Seedling', whereas 'Purple Ais' had the lowest (0.34 kg). The highest SSC was measured in 'Valor' (25.8%), followed closely by that of 'President', 'Stanley', 'Marjorie's Seedling', and 'Purple Ais'. The lowest values were measured in 'Blue Tan' and 'Edwards' (15.8%). TA was highest in 'Blue Tan' (1.54 g/100 mL), followed by 'President', and the lowest in 'Stanley' and 'Valor'. The highest and lowest juice recovery rates were 31.8% and 15.0% in 'Blue Tan' and 'Edwards', respectively. Similar tendencies were observed for fruit weight, fruit firmness, flesh firmness, and SSC in 2009 and 2010 (data not shown). Fruit cracking was not observed in any cultivars. Figure 3 shows the external appearance and transected surface of 8 cultivars. In 'Puchull', 'Purple Ais', 'Blue Tan', and 'Edwards', flesh darkening was observed and some fruits emitted a foul smell. Conversely, such flesh darkening was not observed in 'Stanley', 'Valor', 'President', or 'Marjorie's Seedling'.

Flesh and skin ground color, flesh firmness, SSC, acidity changes, and comparison of waxy bloom levels

Fruit flesh color changes during ripening are shown for 'Purple Ais', 'Edwards', 'Valor', and 'Marjorie's Seedling' in Figure 4. Although flesh color a* values of these 4 cultivars were different, the value in each cultivar gradually increased during maturation and was stable at harvest. In 'Valor' and 'Marjorie's Seedling', flesh color L* and b* values changed from the young to mature stages and stabilized at 40–50 and nearly 30, respectively. In 'Purple Ais' and 'Edwards', flesh color L* and b* values were similar to those of 'Valor' before 110 DAFB, but then decreased before harvest. Namely,

Table 3. Fully ripened fruit quality comparisons of prune cultivars grown in Shimane Prefecture, Japan in 2011.

Cultivar	Fruit weight (g)	Shape	Stone freeness	Firmness		SSC (°Brix)	TA[z] (g/100 mL)	Juice recovery of fruit weight (%)
				Fruit (kg)	Flesh (kg)			
Puchull	54.5 c[y]	Round	Freestone	0.56 c	0.36 cd	19.0 bc	0.93 bc	17.9 abc
Purple Ais	111.9 a	Short-oval	Semi-freestone	0.65 abc	0.34 d	20.0 b	1.06 b	12.8 c
Blue Tan	71.1 bc	Short-oval	Semi-freestone	0.60 bc	0.45 abc	15.5 d	1.54 a	31.8 a
Edwards	117.0 a	Short-oval	Semi-freestone	0.66 ab	0.39 cd	15.8 cd	0.96 bc	15.1 bc
Stanley	56.4 c	Fusiform	Freestone	0.74 a	0.53 a	20.2 b	0.48 d	26.9 ab
Valor	71.2 bc	Fusiform	Freestone	0.60 ab	0.44 bcd	25.8 a	0.49 d	25.7 abc
President	99.9 a	Elliptical	Freestone	0.71 a	0.49 abc	21.1 b	1.11 b	18.9 abc
Marjorie's Seedling	78.3 bc	Short-oval	Semi-freestone	0.66 ab	0.48 abc	20.1 b	0.70 cd	22.2 abc

[z] Titratable acid content was converted to malic acid content.
[y] Different lowercase letters indicate significant differences based on the Tukey–Kramer multiple range test ($P<0.05$).

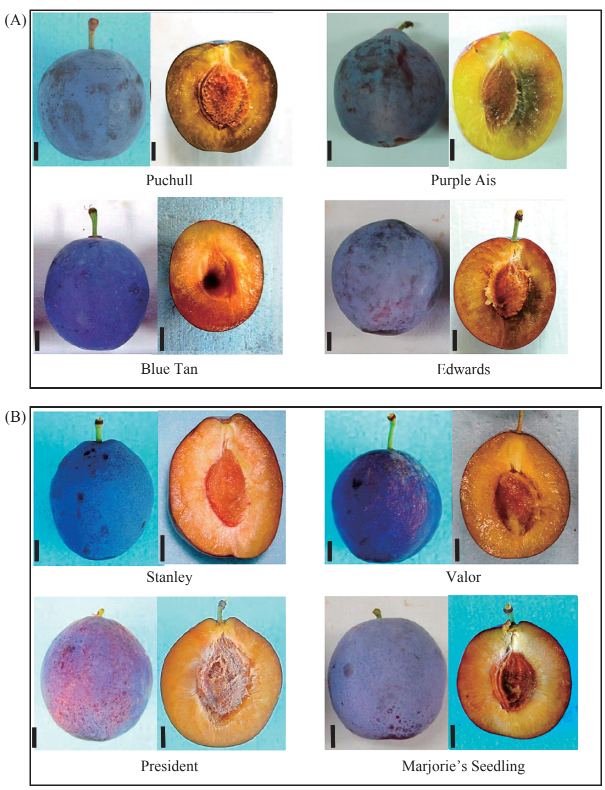

Fig. 3. External and internal appearance of prune fruits grown in Shimane Prefecture, Japan in 2011. Flesh darkening and foul smell occurred in 4 of 8 cultivars (Fig. 3A) but did not occur in the remaining 4 cultivars (Fig. 3B). Vertical bars represent 1 cm.

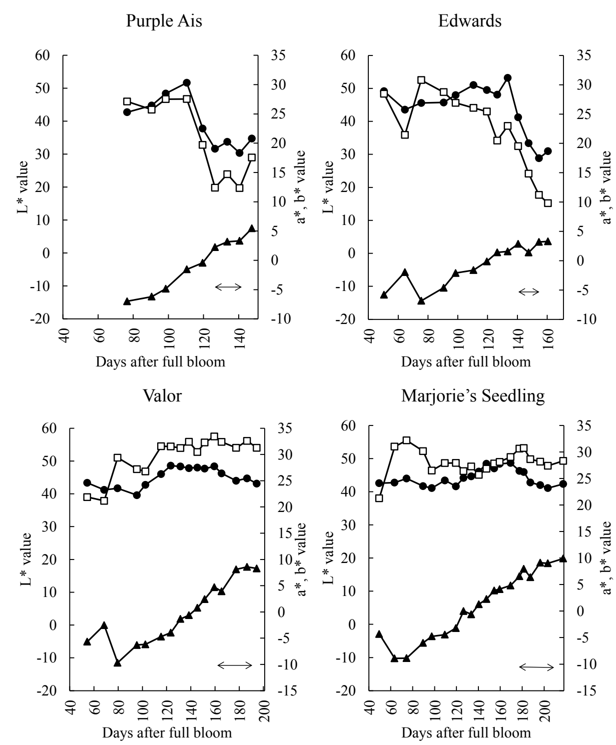

Fig. 4. Time course changes of flesh color evaluated by L*, a*, and b* values of 4 prune cultivars grown in Shimane Prefecture, Japan in 2011 (n = 2 to 3). Horizontal arrows indicate harvesting period. ●, L*; ▲, a*; □, b*.

the 'Valor' flesh color changed from green to yellow to yellow-brown when fully ripened, whereas that of 'Puchull', 'Purple Ais', and 'Edwards' changed from green to yellow to dark brown. The time courses of flesh color changes during maturation of 'Puchull' and 'Blue Tan' were similar to those of 'Purple Ais' and 'Edwards'; those of 'Stanley' and 'President' were similar to 'Valor' and 'Marjorie's Seedling'. Skin ground color changes of 'Purple Ais', 'Edwards', 'Valor', and 'Marjorie's Seedling' during ripening in 2011 are shown in Figure 5. In all four cultivars, the L*/b* value ratios were almost stable at 1 to 2, and then increased before harvest and decreased rapidly at harvest. The h* value, which indicates hue angle, showed stable values of approximately 100, and rapidly decreased before harvest and rapidly increased at harvest.

Changes in flesh firmness, SSC, and pH during ripening of 'Purple Ais', 'Edwards', 'Valor', and 'Marjorie's Seedling' in 2011 are shown in Figure 6. In 'Valor', flesh firmness gradually decreased to 2 kg at 140 DAFB, and then rapidly decreased from 14 days before harvest. Fruit juice pH showed the same trend as

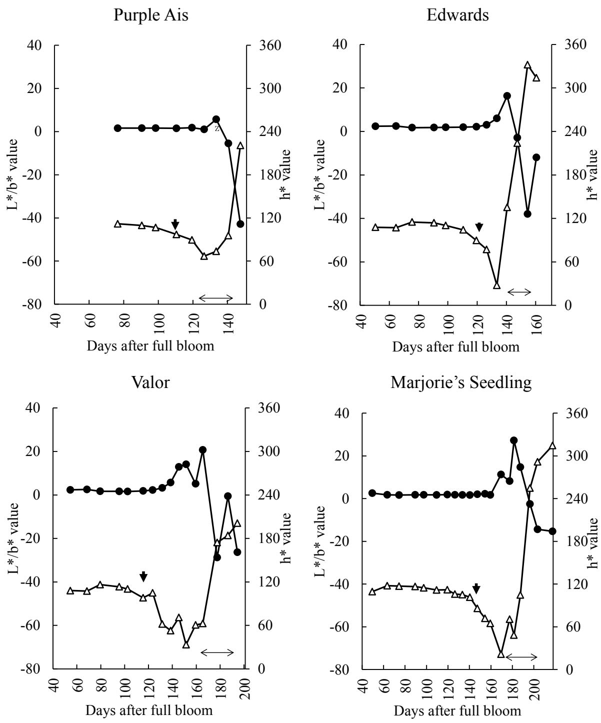

Fig. 5. Time course changes of skin ground color evaluated by L*/b* and h* values of 4 prune cultivars grown in Shimane Prefecture, Japan in 2011 (n = 2 to 3). Arrows indicate onset of coloring. Horizontal arrows indicate harvesting period. ●, L*/b*; △, h*.

flesh firmness in 'Valor', but increased from 14 days before harvest. SSC rapidly increased after 120 DAFB and became stable at harvesting time. A similar phenomenon was also observed in other cultivars. The differences in L* values of skin color before and after waxy bloom removal are shown in Figure 7. As indicated by L* value differences, the waxy bloom amount was high for 'Purple Ais', 'Edwards', and 'Marjorie's Seedling', but was low for 'President'.

Discussion

Relationship between weather conditions during flowering and fruit set

The normal flowering time of prune trees is from early- to mid-March in California (Norton and Kruger, 2009), and flowering can occur earlier in a warm winter (Glozer and Niederholzer, 2007). In case of heavy rainfall, strong wind, or unusually high temperatures during flowering time, poor fruit set may occur. In European prune-producing regions, prune flowering time is generally from late March to early April (Milosevic et al., 2010; Šebek, 2013). However, frost damage during flowering time may reduce fruiting outcomes (Mika et al., 2012; Neumüller, 2011; Yao, 2011). In Izumo, the flowering time is from late March to mid-April, which is during frost season. As shown in Figure 1, the average temperature in March affected flowering time. A higher average temperature in March led to early flowering and may have caused more frost damage. In Saku, the major prune production area in Japan, flowering

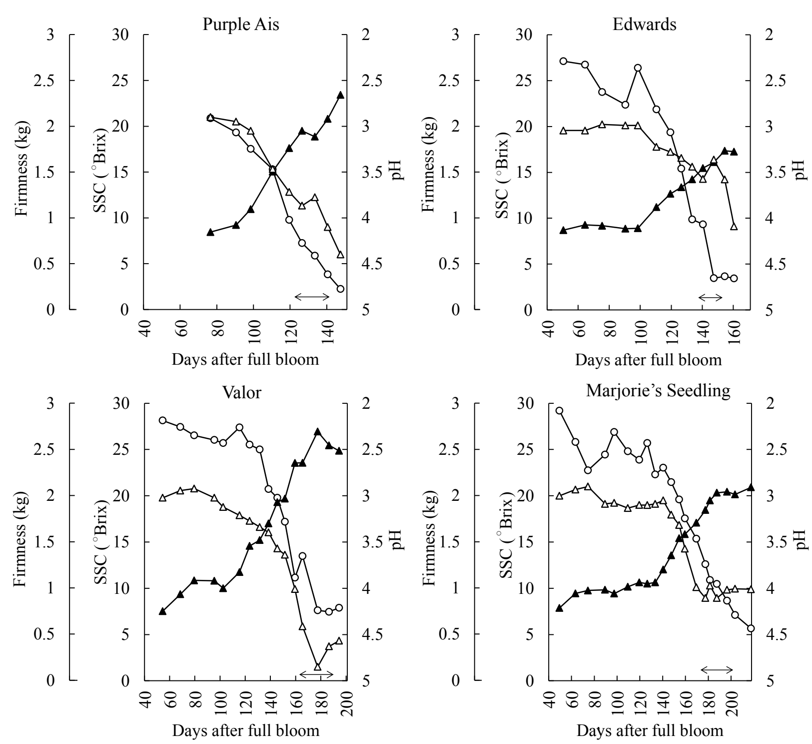

Fig. 6. Time course changes in flesh firmness, SSC, and acidity of 4 prune cultivars grown in Shimane Prefecture, Japan in 2011 (n = 2 to 3). Horizontal arrows indicate harvesting period. ○, Flesh firmness; ▲, SSC; △, pH.

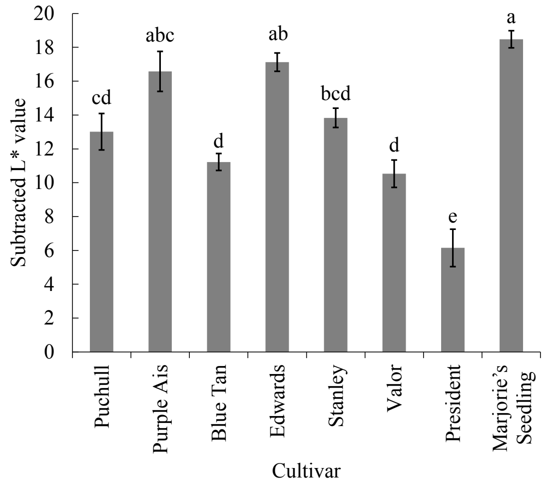

Fig. 7. Skin color difference based on L* values before and after waxy bloom removal of 8 prune cultivars grown in Shimane Prefecture, Japan in 2011. The values were obtained by subtracting the L* value of the fruit skin after waxy bloom removal from that before removal. Vertical bars indicate SE (n = 9 or 10). Different letters indicate significant differences based on the Tukey–Kramer multiple range test ($P < 0.05$).

time is from late April to early May, which is also during frost season in that region. These data indicate the need for frost protection during prune flowering time in general. Of further concern is the strong seasonal winds, which are common to the Izumo area particularly in spring, when winds in excess of $10\,m{\cdot}s^{-1}$ sometime occur (Azukizawa, 2003). In our model experiment area, prune trees were cultivated under rain shelter conditions to prevent poor fruit set due to excessive rainfall or strong winds, and were provided sufficient ventilation to avoid high temperature-induced poor fruit set.

Flowering and pollination requirements

Self-compatible and self-incompatible cultivars are included in commercial prune trees (Hartmann and Neumüller, 2009); therefore, cross pollination is necessary for fruit set in some cultivars. Artificial pollination by brush or insect (such as bees) pollination using different cultivar trees with overlapping flowering periods is effective for fruit set. In cases of early flowering self-incompatible cultivars, collected pollen can be used to pollinate other cultivars at a later time. Prune cultivars with a very early flowering type, short flowering period, and no overlapping flowering period with other cultivars should be avoided because of the resulting poor fruit set. In our experiment, however, flowering periods of all 8 cultivars were relatively close.

In our experiment, 'Puchull' and 'Blue Tan' were self-incompatible cultivars, and their flowering period did not overlap; thus, cross pollination with 'Purple Ais' was desired. However, because the actual flowering time of 'Blue Tan' was early in 2010 and the flowering period was shorter than usual, good fruit set was not expected when planting those 3 cultivars (Fig. 1). These findings indicate that, in cases of self-incompatible cultivars, each orchard should be planted with other cultivars for which flowering times overlap, as either artificial or insect-mediated pollination would be necessary for stable fruit set. The most widely adapted cultivar in California is 'French prune', which is also called 'Prune d'Agen' (Okie and Ramming, 1999). Although it is a self-compatible cultivar, it also utilizes insect pollination by honey bees to achieve stable fruit set and increase fruit production (Vansell and Griggs, 1952).

Suitable cultivars for the temperate monsoon climate zone based on fruit yields and quality

The 4 mid- to late-ripening cultivars we used, 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling', are known to provide high yield (Agriculture and Horticulture Development Board, 2009; Blažek and Pištěková, 2009; Butac et al., 2012; Markuszewski and Kopytowski, 2013; Milosevic et al., 2010). Although the yield in Izumo was low for early-ripening cultivars ('Puchull', 'Purple Ais', and 'Blur Tan'), other countries reported high yields with early-ripening cultivars (Blažek and Pištěková, 2009; Embree et al., 1999). The most important aspect of prune quality is taste, of which preference varies among different countries and individuals (Neumüller, 2011). 'Stanley', 'Valor', and 'President', which are mid- to late-ripening types, have high SSC and favorable taste quality. Although the taste quality of 'Purple Ais' was not very good with regard to low flesh firmness and juice recovery, SSC was high. According to Crisosto (1994), the SSC/TA ratio is more closely related to fruit quality than TA or SSC alone. In 2011, fully ripened fruit of 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling' had high SSC/TA ratios that ranged from 20.0 to 52.8, and had good taste (data not shown). These findings indicate that 'Stanley', 'Valor', 'President', and 'Marjorie's Seedling', which are mid- to late-ripening cultivars, are suitable for table use in a temperate monsoon zone because they produce high yields and good taste quality. Muramatsu and Kojima (2005) reported that 'Purple Ais', 'President', and 'Marjorie's Seedling' are cultivated under rain shelters in the Hokkaido district of a subarctic humid climate zone, indicating the adaptability of these cultivars to that region, and are commercially favored in markets.

Relationship between high-temperature injury and harvesting time

High summer temperatures can result in a phenomenon in which cells of the underlying flesh collapse and darken, which is sometimes found in Japanese and European plums (Neumüller, 2011). Therefore, in our study, the flesh darkening observed in early-ripening cultivars of 'Puchull', 'Purple Ais', and 'Blue Tan' and the mid-ripening cultivar 'Edwards' may be due to high-temperature injury. Additionally, as reported by Neumüller (2011), these cultivars showed partially sunken spots on the fruit skin as a result of high temperature (data not shown). These results show that four cultivars, 'Puchull', 'Purple Ais', 'Blue Tan', and 'Edwards', which matured from mid-August to mid-September, are not suitable for matured fruit production for table use in this temperate monsoon zone.

Our flesh color observation revealed that flesh darkening in prune fruits occurred immediately before harvesting (Fig. 4). However, when harvesting the fruit before flesh darkening, insufficient skin coloring did not provide a good appearance (Fig. 5). In addition, high flesh firmness, high acidity, and low SSC resulted in an unfavorable taste for table use (Fig. 6). Therefore, for table use, we suggest that 'Puchull', 'Purple Ais', 'Blue Tan', and 'Edwards' should not be harvested before flesh darkening. Waxy bloom, which covers the surface of fruits, provides water repellency and inhibits water permeability through the skin (Kolattukudy, 1984). In addition, waxy bloom is known to help maintain fruit quality (Nunes and Emond, 2007). We investigated the possibility of waxy bloom as an index of flesh darkening, but no correlation was found between flesh darkening and waxy bloom level.

Potential for prune cultivation in similar climate regions in other countries and selection of suitable cultivars

The temperature difference between night and day during the ripening stage of fruits is known to be related to an increase in sugar contents (Uematsu et al., 1997) and to improved skin color (Tomana et al., 1979). Major prune production regions of the world, including Saku, Japan, have night and day temperature differences of over 10°C during the fruit ripening stage (July and October in northern hemisphere countries, data not shown). In Izumo, the average night and day temperature differences are 7.8°C, 9.1°C, 9.0°C, and 10.5°C, for July, August, September, and October, respectively, suggesting that prune cultivars having less fruit taste are harvested when average night-day temperature differences were less than 7.8°C in the previous month. According to the Köppen-Geiger climate classification (Peel et al., 2007), humid temperate climate zones include coastal regions of Korea, northern regions of central and south China, eastern and southern regions in the USA, the coastal region of the Black Sea, the eastern region of Australia, and the eastern region of South Africa. Use of rain shelters is recommended for prune tree cultivation in regions with abundant annual rainfall greater than 1200 mm, such as Izumo, Hangzhou in China, Busan in Korea, Atlanta in the USA, and Sochi in Russia. In Atlanta and Sochi, night-day temperature differences are generally greater than 7.8°C throughout the year; therefore, the prune cultivars studied in Izumo are believed to be appropriate. In contrast, as Hangzhou and Busan normally have periods in which the average night-day temperature differences are less than 7.8°C, a choice of other cultivars may be necessary.

Conclusions

In this East Asian temperate monsoon zone, the flowering period of prune trees is from late March to mid-April, and the average temperature in March may lead to earlier or later flowering times. Because the flowering time and frost season may overlap, protection from frost damage is necessary. As flowering time may vary from year to year, in cases of self-incompatible cultivars, each orchard should be planted with other companion cultivars, of which the flowering times overlap, as either artificial or insect-mediated pollination are necessary for stable fruit set. The middle-ripening types 'Stanley' or 'Valor' and late-ripening types 'President' or 'Marjorie's Seedling', which are harvested from mid-September to late October, have high yield and good taste quality. Flesh darkening before harvest occurs as a result of high-temperature injury in 'Puchull', 'Purple Ais', 'Blue Tan', and 'Edwards', which are harvested from mid-August to early September. We suggest that prune fruits for table use can be cultivated in humid temperate climates and the East Asian monsoon zone, as in Izumo, using a rain shelter for mid- to late-ripening cultivars, which mature from mid-September to late-October.

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