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Changes in incidence of fruit cracking, yield, number and characteristics of cherry tomato cultivars developed in Japan during the last 20 years

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Abstract

Changes in the incidence of fruit cracking, yield, number, and characteristics of cherry tomato (*Solanum lycopersicum* L.) in Japan over a 20-years period were investigated. Ten cultivars released in Japan during this period were compared in a short-term experiment conducted from fall through winter in hydroponics. The incidence of fruit cracking in cherry tomato cultivars decreased gradually with year of release from 1987-2009. The incidence of fruit cracking was negatively correlated with fruit yield and number among the 10 cultivars tested. With regard to fruit characteristics, the incidence of fruit cracking was negatively correlated with the fruit weight, the ratio of flesh weight to locular gel weight (F/G), and thickness of exocarp and mesocarp, but not with the flesh weight, soluble solid content or firmness of exocarp and mesocarp among the 10 cultivars tested. These results indicated that, by breeding in cherry tomato cultivars released in Japan over the past two decades, the decreased incidence of fruit cracking was related to the increase in the fruit yield and number per plant, and to the increase in fruit weight and F/G, in association with an increase in the total volume of water inflow into fruits.

Key words: Flesh weight, fruit number, fruit weight, locular gel, *Solanum lycopersicum*

Introduction

Cherry tomatoes have become an important fruit vegetable in many countries. Since fruit cracking is apt to occur in cherry tomatoes, and the fruit yield per plant is lower than that in common tomatoes, growers need to produce higher yields with a reduced number of cracked fruits for maximum profitability (Ohta *et al*., 1991; Halmann and Kobryn, 2003). The marketable fruit yield is reduced by the occurrence of cracked fruits, which do not have commercial value. Therefore, cracking resistance is one of the important factors for breeding in cherry tomatoes. In addition, some consumers demand fruits with high soluble solids content (SSC). If in cherry tomatoes, the number of fruits per truss and/or fruit weight could be increased, an increase in fruit yield could be expected. However, great care must be taken in breeding for these characteristics, since it is possible that SSC would decrease by increasing the fruit weight (Ohta *et al*., 1993b). Moreover, high SSC cultivars are apt to crack due to their reduced osmotic potential resulting increased inflow of water (Ohta *et al*., 1993b).

Because fruit cracking in cherry tomatoes is a major physiological disorder that occurs during the harvest period between the breaker and overripening stages (Domínguez *et al*., 2008; Maboko and du Plooy, 2008; Liebisch *et al*., 2009), as well as during transport after harvest (Lichter *et al*., 2002), it is commercially desirable to reduce the incidence of fruit cracking. However, it would be difficult to decrease fruit cracking to anywhere near 0% in cherry tomatoes because of the movement of water into fruits in which SSC is high (Ohta *et al*., 1993b, 1994). Fruit cracking is also particularly apt to occur in hydroponics, when plant is grown with its roots always immersed in a culture solution (Ohta *et al*., 1993a). Moreover, because Japan receives rainfall of about 1500-2000 mm per year, high air humidity conditions can occur in greenhouses, increasing the likelihood that fruits will crack (Ohta, 1996).

Some researchers (Peet, 1992, 2008; Saltveit, 2005; Kinet and Peet, 2006) have reported that the environmental and physiological causes of fruit cracking in tomatoes are not well understood. They suggested that fruit cracking was related to the environmental and cultivation conditions, and that the anatomical characteristics of crack-susceptible cultivars were large fruit size, low skin (exocarp)-tensile strength, and/or low skin extensibility, as well as thin skin, thin pericarp and/or mesocarp, and few fruits per plant. Although differences in resistance to fruit cracking have been demonstrated among cherry tomato cultivars (Ohta *et al*., 1991; Ohta, 1996), the physiological differences underlying these fruit characteristics have not been fully elucidated. Yamada and Murase (1994) and Ohta (1996) described a strong relationship between fruit cracking and the vascular bundle in mesocarp, which serves as a water pathway in cherry tomatoes (Fig. 1), whereas little information is available about the relationships between the incidence of fruit cracking and several potentially related fruit characteristics, namely, flesh weight (weight minus locular gel), thickness, and firmness.

Although breeders would have made great strides in increasing the cracking resistance of tomato cultivars (Peet, 2008), the genetics of cracking resistance remain poorly understood, because many genes may be involved in the control of this phenomenon (Walter, 1967). Nonetheless, the incidence of fruit cracking in new cherry tomato cultivars in Japan has decreased in more recently released cultivars compared to older cultivars (Nishikawa *et al*., 2005; Matsunaga, 2006). It is presumed that several changes in the cultivation conditions would also contribute to such a decrease, including improvements in greenhouse environmental controls and cultivation techniques, such as relatively higher night temperatures by using heating equipments, and relatively lower humidity achieved with circulation fans. Additionally, because seed companies have performed most of the breeding of cherry tomato cultivars in Japan, one would expect that cultivars with high fruit yield and cracking resistance would have been selected and produced. However, it has not been verified that the fruit yield and incidence of fruit cracking have actually been improved by breeding in Japanese cherry tomato cultivars over the past 20 years.

The aim of this study was thus to investigate whether the cherry tomato cultivars released in Japan from 1987-2009 show changes in the incidence of fruit cracking, fruit yield, number, and certain characteristics when grown under the same conditions. Several parameters that may affect the incidence of fruit cracking are known to be determined by underlying physiological and anatomical characteristics; therefore, the relationships among these traits were also investigated in a short-term experiment conducted from fall through winter in hydroponics.

Materials and methods

Plant materials: The cherry tomato cultivars 'Mini Carol' (Sakata Seed Co., Ltd., Yokohama, Japan), 'Coco' (Takii Co., Ltd., Kyoto, Japan), 'Chika' (Takii Co., Ltd.), 'Sun Cherry 250' (Tokita Seed Co., Ltd., Saitama, Japan), 'Aiko' (Sakata Seed Co.), 'Lovely Ai' (Mikado Kyowa Seed Co., Ltd., Chiba, Japan), 'Lovely Sakura' (Mikado Kyowa Seed Co., Ltd.), 'Kosuzu sp' (Mikado Kyowa Seed Co.), 'Sun Cherry Pure' (Tokita Seed Co., Ltd.), and 'Pinky' (Nanto Seed Co., Ltd., Kashihara, Japan), all of which have been popular in the Japanese market, were used for this experiment. Table 1 lists the year of release, fruit shape, and skin color of mature fruits of the cherry tomato cultivars used in this study.

Experimental site and growing conditions: Seeds were sown in yellowish pumice (diameter 2-5 mm) in plastic containers (34.5 × 27.0 × 7.5 cm) on 16 Aug, 2010 at Shimane University, Matsue, Japan (35°49' N, 133°07' E). All containers were placed in an air-conditioned room with natural light under day/night (0900-1800 HR/1800-0900 HR) temperatures controlled to 28/20 °C, respectively. Seedlings were grown hydroponically for two weeks in plastic containers with 20 L of aerated nutrient solution consisting of half-strength Otsuka-B solution (OAT Agrio Co., Ltd., Tokyo, Japan) with an electrical conductivity of 1.4-1.6 dS m^{-1}. The nutrient solution contained the following elements: 115 mg L^{-1} total nitrogen (TN); 20 mg L^{-1} phosphorus (P); 157 mg L^{-1} potassium (K); 78 mg L^{-1} calcium (Ca); 24 mg L^{-1} magnesium (Mg); 1.5 mg L^{-1} iron (Fe); 0.01 mg L^{-1} copper (Cu); 0.02 mg L^{-1} zinc (Zn); 0.01 mg L^{-1} molybdenum (Mo); 0.39 mg L^{-1} boron (B); and 0.16 mg L^{-1} manganese (Mn).

Tomato plants were then transplanted into a closed irrigation system with a randomized complete block design at a density of 2.2 plants m^{-2} on 13 September, 2010 in a steel-frame greenhouse at Shimane University. Each plot contained five plants. The closed irrigation system consisted of a culture bed with a circulating hydroponic system. The plants were fertilized with a nutrient solution (standard-strength Otsuka-B solution) with an electrical conductivity of 2.0-2.5 dS m^{-1} until the end of harvest. The nutrient solution was supplied for 15 min at 1-h intervals during the day (0600–1800 HR). Concentrations of the nutrients nitrate nitrogen (NO_3^-), phosphate (PO_4^{3-}), K^+, Ca_2^+, and Mg^{2+} in the solution were checked using an RQflex® 10 Reflectoquant® reflectometer (Merck, Germany) twice each week during the experiment, and readjusted as necessary by the addition of concentrated fertilizers. The pH of the nutrient solution was also measured twice weekly, and when necessary, corrected with 1.0 MH_2SO_4 to maintain a pH of 6.0-7.0. The nutrient solution was renewed at 4-week intervals.

Fruit setting was promoted by spraying with 15 mg L^{-1} 4-CPA (4-parachlorophenoxy acetic acid) twice weekly during the flowering period. The average air temperature in the steel-frame greenhouse during the cultivation period was 16.4 ºC, with a maximum temperature of 30.9 ºC and a minimum of 10 ºC maintained after 10 Nov, 2010, using an electric fan heater. All plants were trained vertically, and pinching was performed on the third fruit trusses leaving two leaves. All lateral shoots were periodically removed.

Fruit harvest: Fruits were harvested when they were completely ripe. Fruits from all 10 cultivars were harvested twice weekly between 19 Nov and 20 Dec, 2010.

Table 1. Year of release, fruit shape, and fruit color in cherry tomato cultivars in Japan

Cultivar	Year of release	Fruit shape	Fruit skin color^z			
			L	a	b	a/b^y
Mini Carol	1987	Round	32.4 ± 0.21	21.3 ± 0.31	15.8 ± 0.21	1.35 ± 0.01
Coco	1994	Round	32.8 ± 0.21	23.6 ± 0.60	16.4 ± 0.33	1.45 ± 0.02
Chika	1999	Round	33.2 ± 0.14	24.3 ± 0.48	16.8 ± 0.19	1.45 ± 0.01
Sun Cherry 250	2000	Round	32.5 ± 0.20	22.2 ± 0.81	16.1 ± 0.78	1.40 ± 0.02
Aiko	2004	Oval	33.4 ± 0.35	23.3 ± 0.15	17.1 ± 0.32	1.37 ± 0.03
Lovely Ai	2005	Round	33.1 ± 0.20	22.9 ± 0.46	16.6 ± 0.45	1.38 ± 0.01
Lovely Sakura	2005	Round	32.7 ± 0.40	22.0 ± 0.27	16.4 ± 0.25	1.34 ± 0.01
Kosuzu sp	2005	Round	33.2 ± 0.20	25.1 ± 0.47	16.8 ± 0.27	1.50 ± 0.01
Sun Cherry Pure	2006	Round	33.6 ± 0.29	24.7 ± 1.00	17.1 ± 0.56	1.45 ± 0.03
Pinky	2009	Round	34.2 ± 0.19	27.5 ± 0.25	12.0 ± 0.21	2.31 ± 0.03

^{z} Values are the mean ± SE (n = 46-58). ^{y} a/b indicates maturity.

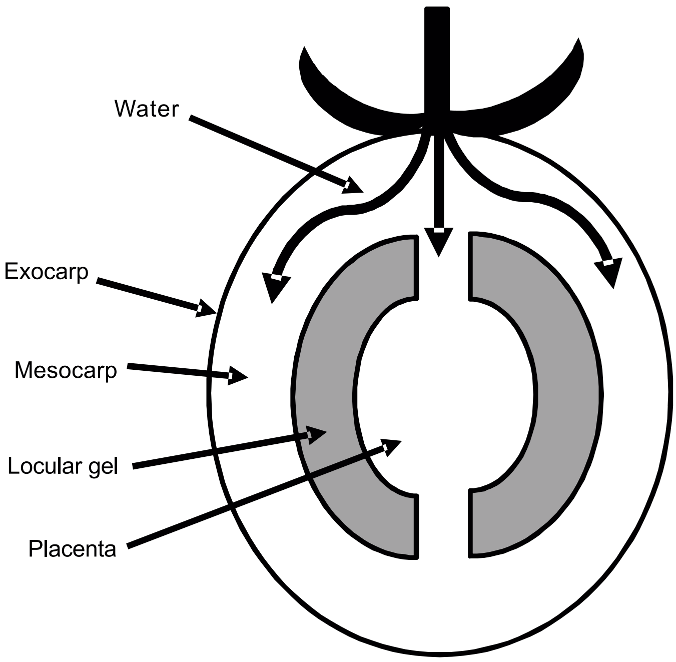

Fig. 1. Fruit anatomy in a longitudinal section of cherry tomato.

Measurements of fruit characteristics: The incidence of fruit cracking was evaluated by checking all harvested fruits. Measurement of fruit characteristics was conducted using 46-58 mature fruits per cultivar. Fruit skin color was measured with a color meter (CR-10, Konica-Minolta Co., Ltd., Tokyo, Japan) and calculated a/b value as maturity. Fruits with a/b value over 1.30 were judged as mature fruits (Ohta, 1996). Fruit weight was determined using an electronic scale. SSC values were evaluated using a digital refractometer (APAL-1, AS ONE Corp., Osaka, Japan) to measure Brix values of fresh juice samples. Fruits were cut into halves, and the locular gel was removed. The skin (exocarp) of one-half of each fruit was peeled with tweezers to measure the thickness of the exocarp and mesocarp. Fruit firmness was estimated at the fruit equator, as described in a previous report (Kamimura *et al.*, 1972), and fruit thickness was measured using digital micrometers (MDC-25MX, Mitsutoyo, Kawasaki, Japan). The firmness of the exocarp and mesocarp of the other half of each fruit was measured using a rheometer (Compac-100, Sun Scientific Co., Ltd., Tokyo, Japan). Fruit was compressed from the inside to the outside with a 3-mm diameter plunger at a compression speed of 40 mm min^{-1}. Penetrating resistance was determined as the point of tissue failure. Data were presented as the maximum force recorded during pericarp compression and failure, according to the method described by Ohta *et al*. (1991).

Statistical analysis: Data were subjected to regression analysis in SPSS ver. 19.0.0 (SPSS, Chicago, IL) at $P = 0.05$ or 0.01, and the differences among means were determined using ANOVA, followed by Tukey's test at $P = 0.05$.

Results

Figure 2 shows the incidence of fruit cracking, yield, and number of fruits for the 10 cultivars. The incidence of fruit cracking tended to decrease gradually in new cultivars among the 10 cultivars released over the period from 1987-2009. The incidence of fruit cracking in 'Mini Carol' and 'Coco', among the earlier cultivars released was high at about 27% and 19%, respectively (Fig. 2a). While, in 'Chika', 'Sun Cherry 250' and 'Aiko', released between 1999 and 2004, it ranged from about 12-25%. In addition, the incidence of fruit cracking was about 7-12% lower in cultivars released during 2005-2009, including 'Lovely Ai', 'Lovely Sakura', 'Kosuzu sp', 'Sun Cherry Pure', and 'Pinky'. Fruit yield in 'Mini Carol', which was released in

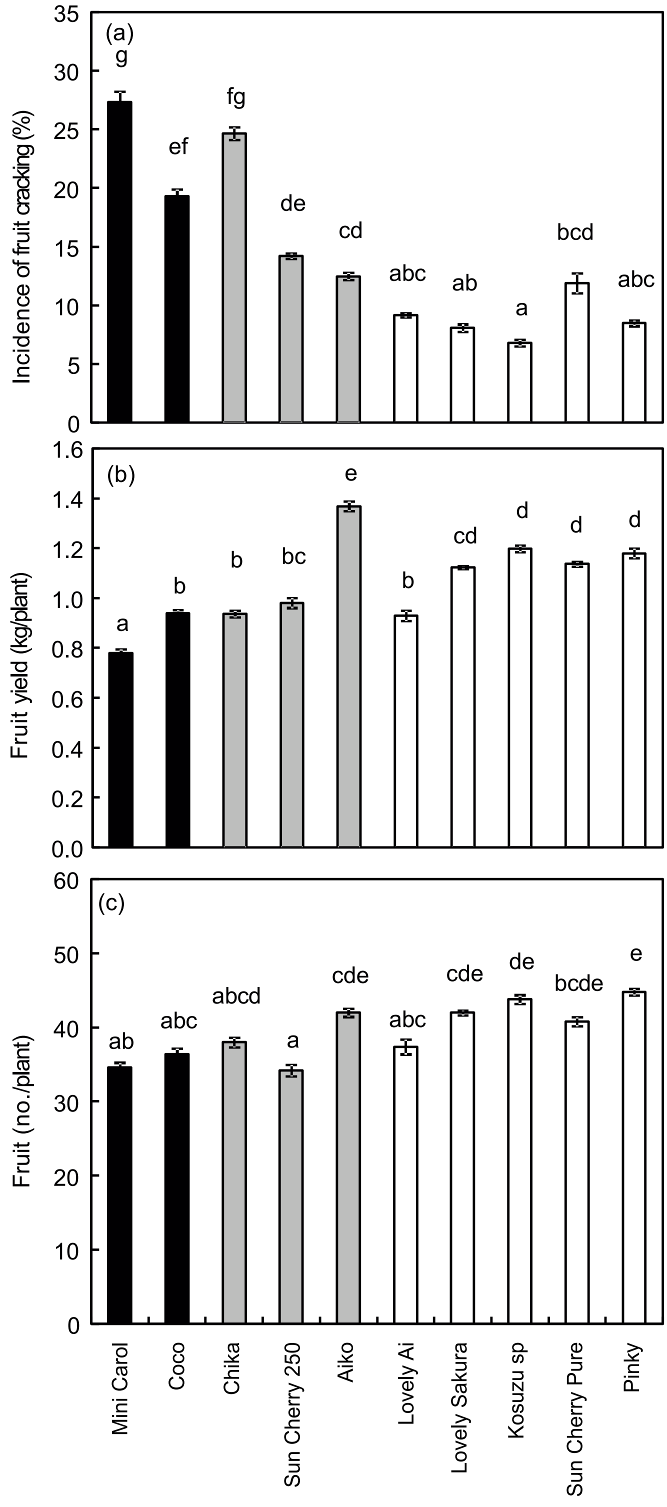

Fig. 2. Incidence of fruit cracking (a), fruit yield (b) and number of fruits (c) for cherry tomato cultivars released in different years in Japan. Letters indicate significant differences by Tukey's test ($P < 0.05$) and vertical bars indicate SE ($n = 5$). ■1987–1994 released cultivars; ▒1999–2004 released cultivars; □2005–2009 released cultivars.

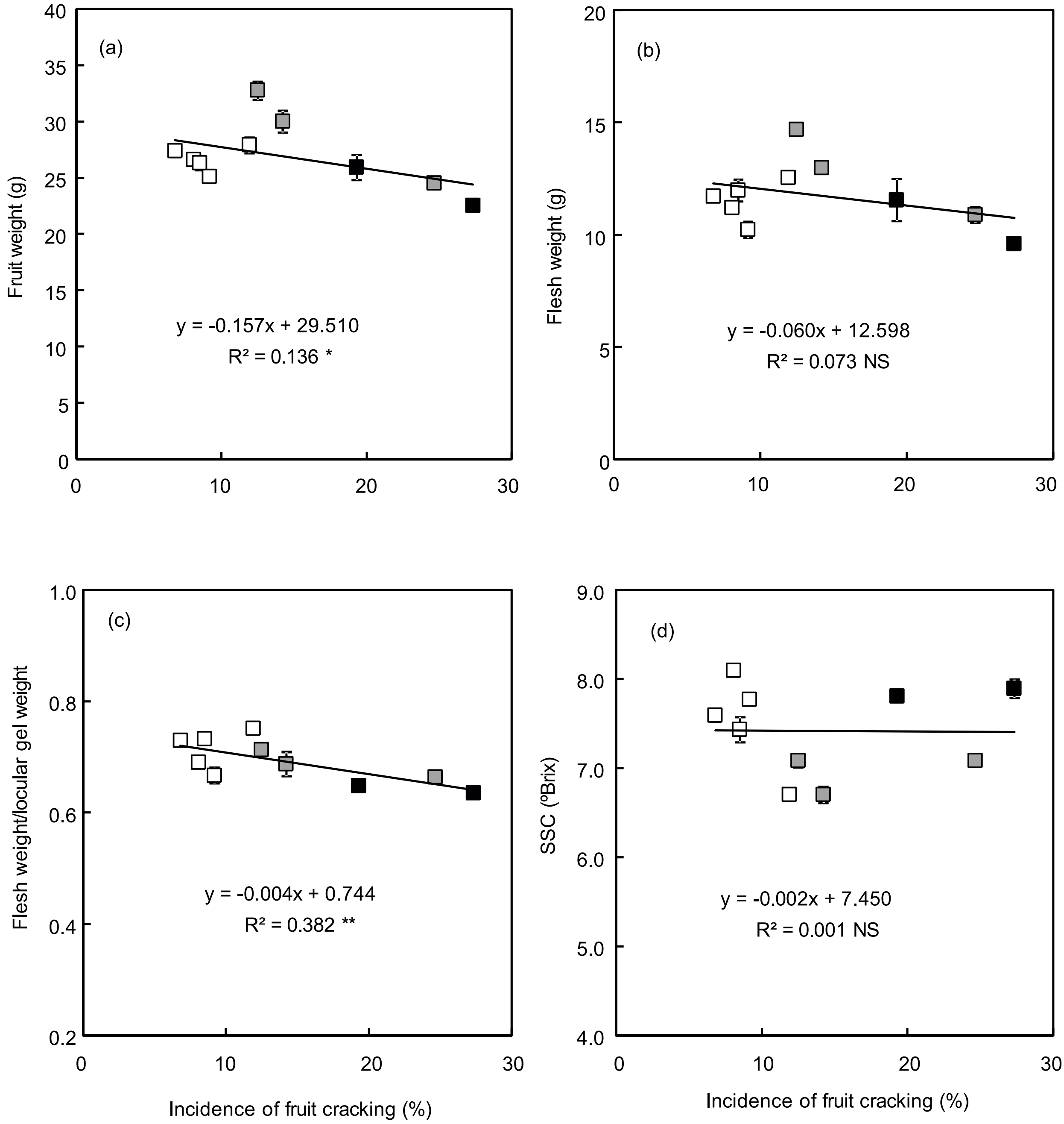

Fig. 3. Regression analysis of fruit weight (a), flesh weight (weight minus locular gel) (b), flesh weight/locular gel weight (F/G) (c), and soluble solids content (SSC) (d) for the incidence of fruit cracking in cherry tomato cultivars released in different years in Japan. Regression lines are based on the data for the 10 Japanese cultivars. NS, * or ** indicate non-significance or significance at $P < 0.05$ or 0.01, respectively, and vertical bars indicate SE (n = 46–58). ■ 1987–1994 released cultivars; ▩ 1999–2004 released cultivars; □ 2005–2009 released cultivars.

1987, was lowest, at 0.78 kg per plant, and that in 'Aiko', released in 2004, was highest, at 1.37 kg per plant (Fig. 2b). Yield in 'Lovely Sakura', 'Kosuzu sp', 'Sun Cherry Pure', and 'Pinky' released between 2005 and 2009, was higher at 1.12-1.20 kg per plant. The number of fruits in 'Mini Carol' and 'Sun Cherry 250', released in 1987 and 2000, were lowest, at 33.8-34.6 fruits per plant, and that in 'Pinky', released in 2009, was highest, at 44.8 fruits per plant (Fig. 2c). Among the 10 cultivars, both fruit yield and number of fruits per plant were significantly negatively correlated with the incidence of fruit cracking (Table 2).

Figure 3 shows the relationship between incidence of fruit cracking and fruit weight, flesh weight, the ratio of flesh weight to locular gel weight (F/G), and SSC in the 10 cultivars tested. The fruit weight and F/G were significantly negatively correlated with the incidence of fruit cracking (Figs. 3a, c); flesh weight and SSC, however, did not show a significant correlation with the incidence of fruit cracking among the 10 cultivars (Figs. 3b, d).

Table 2. Regression analysis for the relation between fruit cracking incidence and fruit yield and number of fruits in cherry tomato cultivars in Japan

Trait	Incidence of fruit cracking		
	Correlation	R^2	Significance
Fruit yield	y = -0.016x + 1.278	0.398	**
Number of fruits	y = -0.364x + 44.536	0.343	**

**Statistically significant at $P < 0.01$.

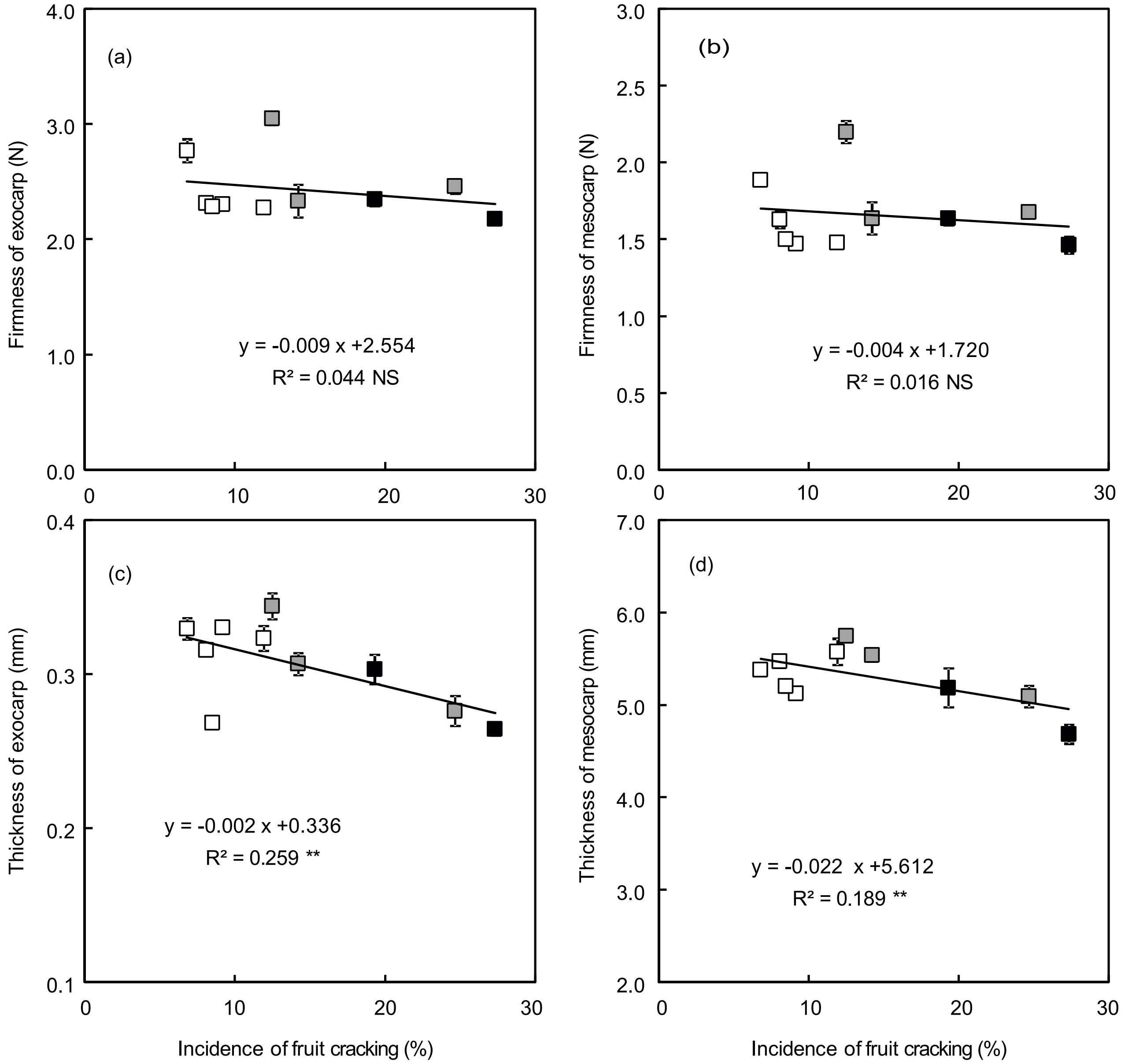

Fig. 4. Regression analysis of the firmness of the exocarp (a) and mesocarp (b) and thickness of the exocarp (c) and mesocarp (d) and their relation to the incidence of fruit cracking in cherry tomato cultivars released in different years in Japan. Regression lines are based on the data for the 10 Japanese cultivars. NS or ** indicate non-significance or significance at $P < 0.01$, respectively, and vertical bars indicate SE (n = 46–58). ■ 1987–1994 released cultivars; ▩ 1999–2004 released cultivars; □ 2005–2009 released cultivars.

Figure 4 shows the relationship between the firmness and thickness of the exocarp and mesocarp for the 10 cultivars tested. The firmness of the exocarp and mesocarp was not correlated with the incidence of fruit cracking (Figs. 4a, b), whereas the thickness of the exocarp and mesocarp was significantly negatively correlated with the incidence of fruit cracking (Figs. 4c, d).

Discussion

Not only fruit cracking, but also low fruit yield were major problems in commercial cherry tomato cultivars introduced in the 1990s in Japan (Ohta *et al.*, 1991; Yamada and Murase, 1994). Therefore, we surmised that one of the most important aims for cherry tomato breeding in Japan has been to obtain fruit-cracking-resistant and high-yield cultivars. The results revealed that, indeed, the cultivars released after 2005 have relatively high fruit-cracking resistance compared to those before 1994 (Fig. 2a), and that fruit yields have improved in the more recently released cultivars. Fruit yield and number of fruits per plant were significantly negatively correlated with the incidence of fruit cracking among 10 cultivars (Table 2). The results of this study indicated that increasing fruit yield and number of fruits per plant which would affect the capacity of water absorption decreased the incidence of fruit cracking.

Fruit weight was significantly negatively correlated with the incidence of fruit cracking among the 10 cultivars (Fig. 3a). In common tomatoes, the incidence of cuticle cracking decreased with increasing fruit yield and number of fruits per plant and/or decreasing fruit size (Emmons and Scott, 1998; Demers *et al.*, 2007). In cherry tomatoes, the incidence of fruit cracking may have been reduced because plants with greater fruit yield, number per plant, and higher fruit weight were better able to distribute an influx of water under high-humidity conditions.

The incidence of fruit cracking in modern cultivars was significantly decreased compared to that in older ones (Fig. 2a). Water moves into fruit along a path through vascular bundles in the fruit flesh, not through the locular gel in tomato fruits (Fig. 1) (Yamada and Murase, 1994). The F/G in modern cultivars was higher than that in older ones. Because the capacity of fruit to absorb water had been increased in modern cultivars, the incidence of fruit cracking might have decreased due to characteristics such as higher extensibility of exocarp, which would allow more water inflow into fruits through the mesocarp and placenta (Ohta *et al*., 1994). Hence, it is suggested that the F/G would be one of the important factors in the incidence of fruit cracking in cherry tomatoes. These results revealed that if the fruit weight and F/G were increased, water absorption capacity would be greater, and fruit cracking-resistance would rise. SSC has not changed much, from 6.7 to 8.1% over the past 20 years (Fig. 3d). Therefore, the result in the present study suggests that the incidence of fruit cracking in high-SSC cherry tomatoes would not be related to SSC, although in low-SSC common tomatoes the incidence of fruit cracking might be related to the difference in SSC.

Since fruit weight in modern cultivars increased compared to that in older cultivars (Fig. 3a), the thickness of exocarp and mesocarp would be increased according to the fruit weight (Figs. 4c, d). Although fruit cracking-resistant cultivars had high fruit exocarp and/or mesocarp firmness in previous studies (Kamimura *et al*., 1972; Saltveit, 2005; Kinet and Peet, 2006; Domínguez *et al*., 2012; Toya *et al*., 2012), the present study did not indicate that these parameters had a clear relationship to the incidence of fruit cracking for the 10 cultivars tested. The cracks on these cherry tomatoes are almost side cracks, and appeared as minute lesions on the surface of the fruit epidermis adjacent to the base of calyx (Ohta *et al*., 1995). Cuticle cracking is a physiological disorder due to decreased exocarp elasticity or extensibility (Allende *et al*., 2004; Dorais *et al*., 2004; Matas *et al*., 2004; Bargel and Neinhuis, 2005). The observed cracks thus might have been the same phenomenon as cuticle cracks. Cuticle cracking-resistant cultivars have thicker epidermal and cuticle layers than susceptible cultivars (Emmons and Scott, 1998). Therefore, the results in this experiment supported the results of previous study. Because the incidence of fruit cracking in the present experiment was not related to the exocarp firmness of cherry tomatoes, the exocarp thickness of modern cherry tomatoes might have provided sufficient strength for cracking resistance of the entire fruit.

In conclusion, the results of this experiment indicated that in cherry tomatoes the decreased incidence of fruit cracking was related to the increase in fruit yield and number per plant, and to the increase in fruit weight and F/G as fruit characteristics, in association with water absorption capacity. Further studies should be undertaken to elucidate the relationships between fruit cracking-resistance and water absorption by plants, as well as the structure of the epidermis in cherry tomato cultivars.

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