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Selection of Crabapple Pollinizers for 'Fuji' and 'Tsugaru' apple[1]

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Abstract

Crabapple cultivars and *Malus* species were examined as pollinizers for two major apple cultivars in Japan: 'Fuji' and 'Tsugaru'. Data on flowering dates, flowering intensity, and cross-compatibility were collected on 19 crabapple cultivars over several years. The following cultivars were selected as potential pollinizers for 'Fuji' and 'Tsugaru': *M. baccata* 79091 and 'Sentinel' for early bloom; *M.* × *atrosanguinea* 20004522, 'Red Bud', and 'Snowdrift' for mid-bloom. All cultivars selected had white flowers with single petals. *M. baccata* 79091 and 'Sentinel' bloomed about 2 to 3 days earlier than 'Fuji' and 'Tsugaru'. Bloom time of terminal buds of *M.* × *atrosanguinea* 20004522, 'Red Bud', and 'Snowdrift' was similar to 'Fuji' and 'Tsugaru'. All selected crabapple cultivars had high bloom density. The percentage of fruit set for all cross combinations between crabapples and commercial cultivars was high. 'Sentinel' coincided with the bloom period of 'Fuji' and 'Tsugaru'. However, 'Sentinel' tended produce fewer seeds per fruit in cross combination with 'Fuji'. The other crabapples that we selected did not overlap with the entire bloom period of 'Fuji' and 'Tsugaru'. Therefore, both an early-blooming pollinizer and a mid-blooming pollinizer should be planted in the same orchards.

The scale of apple (*Malus* × *domestica* Borkh.) orchards in Japan is rather small compared with other countries in the world. Apple growing is very intensive and several commercial cultivars which have higher prices are planted together in orchards for cross-pollination. 'Fuji' is the major late-maturing cultivar in Japan and has become the cultivar with the largest production in the world. The increasing proportion of 'Fuji' and triploid cultivars such as 'Jonagold' in apple orchards has been detrimental to fruit set. Early-maturing cultivars such as 'Tsugaru' and 'Sansa' are often used as pollinizers for 'Fuji'. However, sprays for 'Fuji' to control pests and diseases are sometimes difficult during the harvest time of early-maturing cultivars. Spray drift is also a problem in such cases. There are considerable differences in the necessary cultural practices such as pruning, fruit thinning, plant protection and harvesting among apple cultivars. Single-cultivar orchards enable apple growers to reduce the cost and time for these cultural practices. Therefore there is great interest in single-cultivar orchards using crabapple pollinizers in Japan.

Williams (15) reported that several *Malus* species and a crabapple cultivar appeared worthy as pollinizers for solid plantings of 'Cox's Orange Pippin' in England. Flowering characteristics and compatibility of ornamental *Malus* cultivars with 'Cox's Orange Pippin' were compared (1, 2, 3). 'Golden Hornet', 'Hillieri' 'Winter Gold', and 'Aldenhamensis' were compatible with 'Cox's Orange Pippin' and a combination of two or more of the ornamental *Malus* selections could provide pollen throughout the 'Cox's Orange Pippin' flowering season. Flowering crabapples were evaluated as potential pollinizers for the commercial apple cultivars 'Delicious', 'Jonathan', 'Golden Delicious', 'Gallia Beauty', and 'McIntosh' in the United States (4). Similar studies were conducted in Hungary (12), Sweden (5) and Korea (7).

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The study of crabapple pollinizers for commercial cultivars in Japan has been limited, and some of the promising crabapples in other countries are not available in Japan. Since flowering time is strongly affected by the climate of each apple-producing region, it is important to evaluate the overlap of bloom between crabapples and commercial cultivars under our climatic conditions.

The objectives of the research described here were to determine the flowering biology and fertilizing ability of several crabapple selections, and to select crabapple pollinizers suited for the major apple cultivars in Japan, 'Fuji' and 'Tsugaru'.

Materials and Methods

The study was conducted over the years 2003-2008 using crabapples and *Malus* species available at the Apple Research Station, National Institute of Fruit Tree Science, NARO (Morioka, Japan). All trees were grafted on dwarfing rootstocks (M.9 EMLA or M.26 EMLA). Nineteen crabapples and four apple cultivars were used in this experiment (Table1).

Data of various flowering characteristics were collected in the years 2005-2007 to evaluate the pollinizer potential for 'Fuji' and 'Tsugaru'. The color of flower petals, the number of petals and anthers, and the dates of the following flowering stages were recorded: first bloom of king flower, full bloom of king flower, first bloom of lateral flowers, full bloom of lateral flowers, and petal fall. The axillary flowers were recorded separately from those on spurs or terminal clusters. Flowering density of each tree was scored by observation in 2003 to 2008 as follows: 0 (no flowers), 1 (low), 2 (intermediate), 3 (high), and 4 (extremely high). The coefficient of variation in bloom density by year for each cultivar was calculated to deter-

Table 1. Origin of crabapples and apple cultivars used in this experiment.

Cultivar or clone	Parentage or species
M. × *atrosanguinea* 20004522	*M.* × *atrosanguinea* (Spaeth) Schneid.
Carmine	*M.* × *atrosanguinea* (Spaeth) Schneid.
Jack	*M. baccata* Jackii Rehd.
Japanese	*M. floribunda* Sieb
M. baccata 79091	*M. baccata* (L.) Borkh.
M. turesii T1-3-47	Unknown
Makamik	Open pollinated seedling of *M. pumila niedzwetzkyana* (Dieck) Schneid.
Mandshurica-1	*M. baccata mandshurica* (Maxim.) Schneid.
Maypole	McIntosh Wijcik×Baskatong
Nagasakizumi	*M.* × *micromalus* Mak.
Nepal Apple Col. No. 85-134-2	Unknown
Peachleaf	*M.* × *robusta persicifolia* Rehd.
Profusion 91039	*M.* × *moerlandsii* Doorenbos
Red Splendor	Open pollinated seedling of Red Silver
Red Bud	*M.* × *zumi calocarpa* (Rehd.) Rehd.
Sentinel	Unknown
Shandingzi-1	*M. baccata* (L.) Borkh.
Snowdrift	Unknown
Xifuhaitang	*M.* × *micromalus* Mak.
Fuji	Ralls Janet X Delicious
Indo	Considered to be an open-pollinated seedling of White Winter Pearmain
Orin	Golden Delicious X Indo
Tsugaru	Golden Delicious X Jonathan

mine the tendency for biennial flowering.

Controlled pollinations were made to evaluate the cross-compatibility between commercial cultivars and crabapples in the years 2007-2008. 'Fuji' and 'Tsugaru' were used as the female parents. Pollen from 10 crabapple cultivars and 2 apple cultivars was applied to 'Fuji' and pollen from 7 crabapple cultivars was applied to 'Tsugaru' in May. Flowers of crabapples were collected at the late balloon stage and anthers were harvested and allowed to dehisce at 25°C for 1 or 2 days. Pollen germination was tested on 0.5% agar with 15% sucrose. The percentage of grains to produce pollen tubes was recorded after 2 to 3 hours at room temperature. Observation of 200 pollen grains for germination was done in each cultivar.

One flower of each cluster on all apple cultivars was pollinated at the late balloon stage and the others were removed. For each cross combination, 20 to 40 flowers were pollinated. As the ratio of self-fertilization is quite low, they were not emasculated. Paper bags were used to cover blossoms after crossing to prevent cross-pollination. The number of fruits in the bags was counted and the percentage of fruit set was calculated 3-4 weeks after full bloom. Seeds were isolated from the apple fruit after harvest and the number of seeds per fruit was counted.

Data were subjected to analysis of variance using the Excel Tokei software (Esumi Ltd., Nakano, Tokyo, Japan). The main effects of cultivar and year were tested. Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one degree of freedom test .When treatment effects were significant ($P<0.05$), treatment means were separated by least significant difference (LSD) test.

Results and Discussion

Flower morphology. Flower morphology of 19 crabapples (including *Malus* spp.) and 2 apple cultivars is presented in Table 2. Although most of the crabapple cultivars have

Table 2. Flower morphology of crabapples and apple cultivars in 2007[z].

Cultivar or clone	Petal Color	Petal Number	Anther Number
M. × *atrosanguinea* 20004522	White	5.0±0	20.3±0.1
Carmine[y]	White	-	-
Jack	White	5.3±0.2	21.1±0.4
Japanese	White	5.0±0	19.6±0.2
M. baccata 79091	White	5.0±0	22.5±0.6
M. turesii T1-3-47	White	5.0±0	21.4±0.5
Makamik	Purple	5.0±0	19.9±0.2
Mandshurica-1	White	5.0±0	19.3±0.3
Maypole	Purple	5.0±0	17.6±0.5
Nagasakizumi	White	5.2±0.1	21.7±0.5
Nepal Apple Col. No. 85-134-2	White	5.0±0.1	20.5±0.2
Peachleaf	White	5.0±0	19.7±0.1
Profusion 91039	Purple	5.0±0	19.4±0.4
Red Splendor	Purple	5.0±0	15.8±1.0
Red Bud	White	5.0±0	22.7±0.7
Sentinel	White	5.0±0.1	18.6±0.4
Shandingzi-1	White	5.0±0	20.1±0.1
Snowdrift	White	5.0±0	19.9±0.1
Xifuhaitang	White	5.2±0.1	23.4±0.8
Tsugaru	White	5.0±0	18.9±0.3
Orin	White	5.0±0	18.2±0.5

[z] Values are means ± standard errors (n=20)

[y] Petal number and anther number of 'Carmine' were not recorded, but it had a single flower.

Table 3. Relative blooming period[z] of terminal buds in crabapple cultivars and 'Tsugaru' with 'Fuji' in 2005-2007.

Cultivar or clone	King flower		Lateral flower		Petal fall of terminal bud
	First bloom	Full bloom	First bloom	Full bloom	
Nepal Apple Col. No. 85-134-2	-4.5[z] a[y]	-5.8 a	5.2 a	-6.7 a	-4.8 a
Mandshurica-1	-3.3 ab	-3.9 bc	-3.3 abc	-4.5 b	0.6 efg
Xifuhaitang	-3.2 ab	-4.3 ab	-3.8 ab	-4.2 bc	-3.3 ab
M. baccata 79091	-2.7 bc	-3.3 bcd	-3.3 abc	-4.3 bc	-1.2 bcde
Red Splendor	-2.5 bc	-2.7 bcde	-1.8 cde	-2.5 cdef	-0.7 cde
Nagasakizumi	-2.4 bc	-4.1 abc	-2.2 bcd	-3.2 bcd	-1.7 bcde
Maypole	-1.8 bcd	-3.0 bcd	-2.8 bc	-3.7 bcd	-2.0 abc
Peachleaf	-1.8 bcd	-2.3 cde	-1.8 cde	-3.2 bcd	-2.5 abc
Makamik	-1.7 bcde	-1.7 defg	-2.3 bcd	-1.7 defg	-1.0 bcde
Sentinel	-1.7 bcde	-2.0 def	-1.5 cdef	-1.8 defg	2.3 fgh
Jack	-1.3 cdef	-2.0 def	-1.7 cdef	-2.7 bcde	-1.3 bcde
Shandingzi-1	-1.3 cdef	-3.0 bcd	-2.3 bcd	-4.7 b	-1.7 bcde
Japanese	-0.3 defg	-1.0 efgh	-0.5 defg	0.0 ghi	3.7 h
Profusion 91039	0.2 fg	-0.5 fghi	0.0 efgh	-1.0 efgh	2.7 gh
Carmine	1.0 gh	-0.3 fghi	0.2 fgh	-1.0 efgh	3.7 h
M. turesii T1-3-47	1.1 gh	-0.3 fghi	0.8 gh	-0.3 ghi	0.5 efg
Red Bud	2.2 h	0.8 i	1.0 gh	-0.5 fghi	4.0 h
Snowdrift	2.3 h	0.8 i	1.7 h	0.0 ghi	3.7 h
M. × *atrosanguinea* 20004522	1.2 gh	0.0 ghi	0.7 gh	1.2 i	4.3 h
Tsugaru	0.0 efg	-0.3 fghi	1.0 gh	1.0 hi	2.3 fgh
Fuji	0.0 efg	0.0 ghi	0.0 efgh	0.0 ghi	0.0 def
Fuji (average blooming dates)	May 13	May 17	May 15	May 19	May 23
Significance[x]					
Cultivar	**	**	**	**	**
Year	**	**	**	**	NS
Cultivar X Year[w]	NS	**	*	*	**

[z] Data indicates deviation from bloom date of 'Fuji'
[y] Mean separation within columns by least significant difference (LSD) test at P=0.05
[x] NS, *,** = nonsignificant, P=0.05, P=0.01, respectively
[w] Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one-degree of freedom test .

white single petals, 'Makamik', 'Maypole', 'Profusion 91039', and 'Red Splendor' have purple petals. These cultivars have a pedigree that includes *M. pumila* var. *niedzwetzkyana* Schneider (the source of a gene that confers red leaves). Mayer et al. (11) stated that honey bees showed a strong fidelity to foraging on either non-white or white flowers. Therefore, crabapples with white petals are better than those with purple petals when honeybees are used as pollinators in the orchard. Honeybees and horned-face bees (*Osmia cornifrons* Radoszkowski) are utilized as pollinators in Japan, although the foraging behavior of horned-face bees on purple flowers is unknown. All of the crabapple cultivars evaluated in this study are single-flowered, and the numbers of petal is around 5. Anther number of the crabapples ranged from 15 to 23. The number of anthers in Xifuhaitang, 'Red Bud', and *M. baccata* 79091 tended to be high.

Blooming period. Relative blooming period (deviation from 'Fuji') of terminal buds in crabapples and 'Tsugaru' is presented in Table 3. 'Fuji' bloom started on May 13 (mean of 3 years, 2005-2007). Full bloom of king flowers

was on May 17 and that of lateral flowers was on May 19. The blooming period of 'Tsugaru' was similar to that of 'Fuji'. First bloom of king flowers of Nepal Apple Col. No. 85-134-2, Mandshurica-1, Xifuhaitang, *M. baccata* 79091, 'Red Splendor', Nagasakizumi, 'Maypole', and 'Peachleaf' was significantly earlier than that of 'Fuji'. The interaction of cultivar and year was significant for full bloom of king flowers, lateral flowers and petal fall. The differences among cultivars in date of full bloom for king flowers were small in 2006, while these differences were large in 2005 and 2007 (Table 4). Yearly changes in blooming period for Nepal Apple Col. No. 85-134-2, Xifuhaitang, Nagasakizumi, and Mandshurica-1 were especially large. These cultivars, for which the bloom periods change according to yearly climatic conditions, are not suitable for pollinizers. All data, except those for these four cultivars, were subjected to ANOVA and no interaction between cultivar and year was found (data not shown). Full bloom of king flowers in terminal buds of *M. baccata* 79091, Shandingzi-1, 'Maypole', 'Red Splendor' 'Peachleaf', 'Sentinel' and 'Jack' are earlier than 'Fuji' without the large yearly changes (Table 4). Full bloom of lateral flowers in terminal buds of Shandingzi-1, *M. baccata* 79091, 'Maypole', 'Peachleaf', 'Jack', and 'Red Splendor' are earlier than 'Fuji' without the large yearly changes. The date of petal fall of Nepal Apple Col. No. 85-134-2, Xifuhaitang, 'Peachleaf' and 'Maypole' tended to be earlier than that of 'Fuji' (Table 3). Yearly changes in petal fall date for Nepal Apple Col. No. 85-134-2, 'Peachleaf', 'Profusion 91039', *M. baccata* 79091 and 'Japanese' were large (data not shown).

Relative blooming period (deviation from

Table 4. Yearly changes in bloom period of terminal buds (2005-2007).

	Full bloom of king flower				Full bloom of lateral flower			
Cultivar or clone	2005	2006	2007	Average[z]	2005	2006	2007	Average[z]
Nepal Apple Col. No. 85-134-2	-7	-2.5	-8	-5.8±1.7	-8	-3.7	-8.5	-6.7±1.5
Xifuhaitang	-7	-1.5	-4.5	-4.3±1.6	-6.5	-3	-3	-4.2±1.2
Nagasakizumi	-7.3	-0.7	-4.3	-4.1±1.9	-7	-1.3	-1.3	-3.2±1.9
Mandshurica-1	-6	-1	-4.7	-3.9±1.5	-8	-2.3	-3.3	-4.5±1.8
M. baccata 79091	-4	-1.5	-4.5	-3.3±0.9	-5.5	-3.5	-4	-4.3±0.6
Maypole	-4	-1	-4	-3±1	-4	-3	-4	-3.7±0.3
Shandingzi-1	-3	-2	-4	-3±0.6	-6	-4	-4	-4.7±0.7
Red Splendor	-4.5	-0.5	-3	-2.7±1.2	-3	-2	-2.5	-2.5±0.3
Peachleaf	-3	-1	-3	-2.3±0.7	-3.5	-2	-4	-3.2±0.6
Jack	-2	-1	-3	-2±0.6	-3	-2	-3	-2.7±0.3
Sentinel	-3	-1	-2	-2±0.6	-2	-1.5	-2	-1.8±0.2
Makamik	-3	0	-2	-1.7±0.9	-2	-1	-2	-1.7±0.3
Japanese	-2	0.5	-1.5	-1±0.8	-2.5	2	0.5	0±1.3
Profusion 91039	0	0.5	-2	-0.5±0.8	-1	-1	-1	-1±0
M. turesii T1-3-47	0.5	0.3	-1.7	-0.3±0.7	-1	-1	1	-0.3±0.7
Carmine	-0.5	0.5	-1	-0.3±0.4	-2	-0.5	-0.5	-1±0.5
M. × *atrosanguinea* 20004522	0	1	-1	0±0.6	-1	2	2.51	2±1.1
Red Bud	1.5	1	0	0.8±0.4	-0.5	-0.5	-0.5	-0.5±0
Snowdrift	1	1.50		0.8±0.4	0	-1	1	0±0.6
Tsugaru	0	1	-2	-0.3±0.9	1	1	1	1±0
Fuji	0	0	0	0±0	0	0	0	0±0
Average	-2.5	-0.4	-2.7	-1.9	-3.1	-1.3	-1.8	-2.1

[z] Values are means ± standard errors (n=3)

Table 5. Relative blooming period of axillary buds in crabapple cultivars and 'Tsugaru' with 'Fuji' in 2005-2007.

	King flower		Lateral flower		Petal fall of
Cultivar or clone	First bloom	Full bloom	First bloom	Full bloom	axillary bud
Nepal Apple Col. No. 85-134-2	-8.7[z] a[y]	-8.0 a	-8.7 a	-8.2 a	-5.8 a
Xifuhaitang	-6.8 ab	-6.3 ab	-7.3 ab	-5.8 bcd	-5.3 ab
M. baccata 79091	-6.3 b	-6.3 ab	-6.0 bc	-7.2 ab	-4.3 abc
Nagasakizumi	-6.3 b	-6.3 ab	-5.5 bcd	-6.0 bcd	-4.6 abc
Mandshurica-1	-6.2 b	-5.7 b	-5.5 bcd	-5.2 cde	-2.0 e
Makamik	-5.7 bc	-5.3 bc	-4.0 cdef	-4.7 cde	-4.0 abcd
Red Splendor	-5.3 bcd	-4.7 bcd	-4.8 cde	-4.3 de	-2.8 cde
Shandingzi-1	-5.0 bcd	-6.0 ab	-6.0 bc	-6.3 abc	-5.0[v]
Jack	-3.7 cde	-4.3 bcde	-3.7 defg	-5.0 cde	-4.3 abc
Sentinel	-3.3 def	-3.5 cdef	-2.7 efgh	-4.2 def	0.3 f
Peachleaf	-3.2 defg	-2.8 defg	-2.8 efgh	-4.2 def	-3.7 bcde
Carmine	-2.5 efg	-2.3 efgh	-2.8 efgh	-2.0 gh	1.0 f
M. × *atrosanguinea* 20004522	-2.3 efg	-1.8 fghi	-1.7 ghi	-1.5 hi	1.0 f
Japanese	-2.2 efgh	-2.5 efgh	-2.2 fghi	-2.3 fgh	0.7 f
M. turesii T1-3-47	-1.9 efgh	-2.2 fgh	-1.6 ghi	-3.8 efg	-2.4 de
Maypole	-1.7 efgh	-2.7 defg	-1.3 hi	-3.7 efg	-4.0 abcd
Profusion 91039	-1.3 fgh	-0.5 hi	-0.8 hi	-0.7 hi	0.5 f
Red Bud	-1.2 fgh	-0.8 ghi	-1.8 fghi	-1.7 hi	0.3 f
Snowdrift	-1.0 gh	-1.0 ghi	-1.2 hi	-1.7 hi	0.2 f
Tsugaru	-1.0 gh	1.3 j	-0.3 i	1.3 j	1.0[v]
Fuji	0.0 h	0.0 ij	0 i	0.0 ij	0.0 f
Fuji (average bloom date)	May 18	May 20	May 19	May 23	May 27
Significance[x]					
Cultivar	**	**	**	**	**
Year	**	NS	**	**	**
Cultivar X Year[w]	**	**	**	*	**

[z] Data indicates deviation from the bloom date of 'Fuji'
[y] Mean separation within columns by least significant difference (LSD) test at P=0.05
[x] NS, *,** = nonsignificant, P=0.05, P=0.01, respectively
[w] Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one-degree of freedom test.
[v] Average for 2 years

'Fuji') of axillary buds is presented in Table 5. 'Fuji' bloom started on May 18. Full bloom of king flowers was on May 20 and that of lateral flowers was on May 23. The interaction of cultivar and year was significant in relative blooming period of both types of axillary buds (Table 5). The blooming period of crabapple and apple cultivars in 2006 was shorter than that in 2005 and 2007 (Table 6). The differences of full blooming date of king flower among cultivar in 2006 were small, while the differences of blooming date among cultivars were large in 2005 and 2007 (Table 6). Full bloom of king flowers of Nepal Apple Col. No. 85-134-2, Xifuhaitang , *M. baccata* 79091, Nagasakizumi, Shandingzi-1, Mandschurica-1, 'Makamik', 'Red Splendor', 'Jack', 'Sentinel', 'Peachleaf', 'Maypole', 'Japanese', 'Carmine' and *M. turesii* T1-3-47 tended to be earlier than that of 'Fuji'(Table 5). Yearly changes of blooming period of Nepal Apple Col. No. 85-134-2, Xifuhaitang,

Nagasakizumi, Shandingzi-1, Mandshurica-1, 'Profusion 91039', and 'Tsugaru' were large (Table 6). Full bloom of lateral flowers of 'Nepal Apple Col. No. 85-134-2, *M. baccata* 79091, Shandingzi-1, Nagasakizumi, Xifuhaitang , Mandschurica-1, 'Jack', 'Makamik', 'Red Splendor', 'Sentinel', 'Peachleaf', *M. turesii* T1-3-47 , 'Maypole', 'Japanese', and 'Carmine' tended to be earlier than that of 'Fuji'(Table 5). Yearly changes of blooming period of Nepal Apple Col. No. 85-134-2, Nagasakizumi, *M. baccata* 79091, Shandingzi-1, 'Makamik', 'Red Splendor', 'Jack', 'Sentinel', 'Peachleaf', 'Japanese', *M. turesii* T1-3-47, and 'Snowdrift' were large (Table 6). Petal fall of 'Fuji' was on May 27. The date of petal fall of Nepal Apple Col. No. 85-134-2, Xifuhaitang, Nagasakizumi, '*M. baccata* 79091, 'Jack', 'Makamik', 'Maypole', Peachleaf' 'Red Splendor', *M. turesii* T1-3-47 , and Mandschurica-1 was earlier than that of 'Fuji'(Table 5). Yearly changes of petal fall of Nepal Apple Col. No. 85-134-2, *M. baccata* 79091, 'Makamik', 'Red Splendor', Mandschurica-1, and 'Profusion 91039' were large (data not shown).

The flowering periods of crabapples, *Malus* spp., 'Fuji' and 'Tsugaru' are presented in Fig. 1. We arranged 20 cultivars into two groups for bloom period. 'Jack', *M. baccata* 79091 , 'Makamik', Mandschurica-1, 'Maypole', Nagasakizumi, Nepal apple Col.85-134-2, 'Peachleaf', 'Red Splendor', 'Sentinel', Shandingzi-1 and Xifuhaitang were early-blooming cultivars that bloomed about 1 to 3 days earlier than 'Fuji' and 'Tsugaru'. *M.* × *atrosanguinea* 20004522, 'Carmine', 'Japanese', *M. turesii* T1-3-47, 'Profusion 91039', 'Red Bud', and 'Snowdrift' were mid-blooming cultivars similar to 'Fuji' and 'Tsugaru'.

Table 6. Yearly changes in bloom period of axillary buds (2005-2007).

	Full bloom of king flower				Full bloom of lateral flower			
Cultivar or clone	2005	2006	2007	Average[z]	2005	2006	2007	Average[z]
Nepal Apple Col. No. 85-134-2	-9	-6	-9	-8±1	-8.5	-5.5	-11	-8.2±1.5
Xifuhaitang	-8.5	-4.5	-6	-6.3±1.2	-5.5	-5	-7	-5.8±0.6
Nagasakizumi	-7.7	-4.3	-7	-6.3±1.0	-7	-4	-7	-6±1
M. baccata 79091	-6.5	-5.5	-7	-6.3±0.4	-6	-6	-9.5	-7.2±1.2
Shandingzi-1	-5	-5	-8	-6±1	-4	-6	-9	-6.3±1.5
Mandshurica-1	-7	-3.7	-6.3	-5.7±1	-4	-4.7	-7	-5.2±0.9
Makamik	-7	-4	-5	-5.3±0.9	-3	-4	-7	-4.7±1.2
Red Splendor	-5.5	-4	-4.5	-4.7±0.4	-2	-3.5	-7.5	-4.3±1.
Jack	-4	-4	-5	-4.3±0.3	-3	-5	-7	-5±1.2
Sentinel	-3	-3.5	-4	-3.5±0.3	-2	-3.5	-7	-4.2±1.5
Peachleaf	-2.5	-3	-3	-2.8±0.2	-2.5	-4	-6	-4.2±1.0
Maypole	-2	-3	-3	-2.7±0.3	-2	-4	-5	-3.7±0.9
Japanese	-3	-1.5	-3	-2.5±0.5	-2	-0.5	-4.5	-2.3±1.2
Carmine	-3	-1.5	-2.5	-2.3±0.4	-2	-0.5	-3.5	-2±0.9
M. turesii T1-3-47	-1	-2.7	-3	-2.2±0.6	-1	-3.3	-7	-3.8±1.7
M. × *atrosanguinea* 20004522	-2	-1	-2.5	-1.8±0.4	-2	0	-2.5	-1.5±0.8
Snowdrift	-0.5	-1	-1.5	-1±0.3	0	-1	-4	-1.7±1.2
Red Bud	-0.5	-1.5	-0.5	-0.8±0.3	-0.5	-2	-2.5	-1.7±0.6
Profusion 91039	-2	-1.5	2	-0.5±1.3	0	-1.5	-0.5	-0.7±0.4
Tsugaru	0	0	4	1.3±1.3	3	1	0	1.3±0.9
Fuji	0	0	0	0±0	0	0	0	0±0
Average	-3.8	-2.9	-3.6	-1.9	-2.6	-3	-5.4	-3.7

[z] Values are means ± standard errors (n=3)

The speed of bloom in most crabapples in this experiment was faster than that of commercial cultivars; consequently, the duration of the bloom period from the first bloom to full bloom of crabapple cultivars was shorter than commercial cultivars.

Fruits from the terminal buds are larger than fruits from axillary buds. Therefore, fruit set of flowers of terminal buds especially king flowers is important. It takes about a day to release the pollen after bloom and takes about 3-4 days to reach the peak of dehiscence after bloom (3). Cultivars suggested as pollinizers in orchards should start to bloom 1 to 2 days earlier than the main fruiting cultivars (13). Following this criterion, early-blooming cultivars such as 'Red Splendor', 'Peachleaf', 'Jack', 'Makamik', 'Sentinel' and 'Maypole' might be effective for pollination of flowers of terminal buds of 'Fuji'. Their axillary flowers are also useful for pollination of 'Fuji' and 'Tsugaru' (Fig. 1). *M. baccata* 79091, Xifuhaitang, Mandschurica-1, Nagasakizumi and Shandinzi-1 bloom overlapped with that of the king flowers of terminal buds of 'Fuji' or 'Tsugaru', and the smaller fruit from axillary flowers of 'Fuji' and 'Tsugaru' would not have to be thinned at a later date. However, the blooming period of some crabapple cultivars fluctuates by year; they sometimes bloom too early to set the flowers of 'Fuji' and 'Tsugaru'. In contrast, *M.* × *atrosanguinea* 20004522, 'Carmine', 'Red Bud' and 'Snowdrift' started to bloom 1 to 3 days later than 'Fuji', which may be too late to cover the king bloom of 'Fuji' and 'Tsugaru'. These data suggest that early-blooming cultivars such as *M. baccata* 79091 and Nagasakizumi should be used as pollinizers together with mid-blooming cultivars to cover the entire bloom period of 'Fuji' and 'Tsugaru'.

Bloom density and regularity of flowering. Bloom density and regularity of flowering in crabapples and *Malus* spp. are presented in Table 7. Bloom density of terminal buds ranged from 2.0 (intermediate) to 3.8 (abundant). 'Makamik' and 'Sentinel' had higher bloom density than Nagasakizumi, Mandshurica-1, Peachleaf, Profusion 91039, Nepal Apple Col. No. 85-134-2, Shandingzi-1, 'Jack', 'Japanese', Xifuhaitang and *M. baccata* 79091 (Table 7). 'Carmine', 'Snowdrift', 'Red Bud', *M.* × *atrosanguinea* 20004522, 'Sentinel' and Xifuhaitang had higher bloom density of axillary flowers than 'Peachleaf', Nepal Apple Col. No. 85-134-2, 'Jack', 'Japanese', and 'Maypole'. The coefficient of variation of bloom density by year indicates the regularity of flowering. The tendency for biennial flowering in terminal buds was very high in Nepal Apple Col.85-134-2 and 'Peachleaf', and high in Mandshurica-1, Shandingzi-1 and 'Jack'. However, 'Makamik', 'Sentinel', 'Carmine', 'Snowdrift', 'Profusion 91039' and Xifuhai-

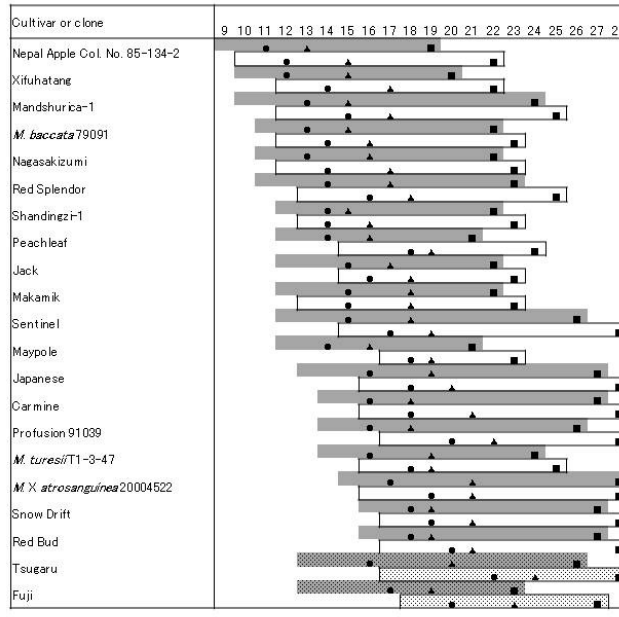

Fig. 1 Average dates of flower opening of 'Tsugaru', 'Fuji' and crabapples in 2005–2007.

Table 7. Bloom density and regularity of flowering in crabapple varieties (2003-2008).

Cultivar or clone	Bloom intensity				Coefficient of variation of bloom intensity	
	Terminal bud		Axillary bud		Terminal bud	Axillary bud
Nagasakizumi	2.0	a[z]	2.5	defghi	0.17	0.10
Mandshurica-1	2.1	ab	2.5	cdefghi	0.23	0.29
Peachleaf	2.1	ab	1.6	abc	0.37	0.45
Profusion 91039	2.2	abc	2.3	bcdefg	0.08	0.06
Nepal Apple Col. No. 85-134-2	2.2	abc	1.7	abcd	0.40	0.37
Shandingzi-1	2.3	abc	2.6	defghi	0.22	0.17
Jack	2.4	abc	1.6	ab	0.29	0.36
Japanese	2.5	abcd	1.8	bcde	0.13	0.27
Xifuhaitang	2.5	abcd	2.8	fghi	0.09	0.17
M. baccata 79091	2.7	abcd	2.6	defghi	0.16	0.21
Maypole	2.9	abcde	0.9	a	0.12	0.35
M. × *atrosanguinea* 20004522	2.9	abcdef	2.9	ghi	0.12	0.16
Red Bud	2.9	abcdef	3.2	ghi	0.13	0.10
M. turesii T1-3-47	3.0	bcdef	2.0	bcdef	0.14	0.30
Red Splendor	3.0	cdef	2.4	bcdefgh	0.15	0.19
Snowdrift	3.1	cdef	3.3	hi	0.07	0.10
Carmine	3.3	def	3.4	i	0.06	0.08
Makamik	3.8	ef	2.7	efghi	0.05	0.09
Sentinel	3.8	f	2.8	fghi	0.05	0.12
Significance[y]						
Cultivar	**		**			
Year	NS		**			
Cultivar X Year[x]	NS		NS			

[z] Mean separation within columns by least significant difference (LSD) test at P=0.05

[y] NS, ** = nonsignificant, P=0.01, respectively

[x] Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one-degree of freedom test.

tang had annual flowering. The tendency for biennial flowering in axillary buds was higher than that in terminal buds. The tendency for biennial flowering in axillary buds was very high in 'Peachleaf', 'Nepal Apple Col. No. 85-134-2' 'Jack' and 'Maypole', and high in *M. turesii* T1-3-47, Mandschurica-1, and 'Japanese'. 'Profusion 91039', 'Carmine' and 'Makamik' had regular axillary flowering. In regards to overlapping with the bloom period of 'Fuji', bloom density of flowers of axillary and terminal buds is important for early blooming cultivars, and bloom density of flowers of terminal buds is more important for mid-blooming cultivars. The flowers of axillary buds of Nagasakizumi, 'Mandshurica-1, Shandingzi-1, Xifuhaitang, *M. baccata* 79091, 'Red Splendor', 'Makamik', and 'Sentinel' might be useful for pollination of 'Fuji'. The flowers of terminal bud of 'Maypole', *M.* X *atrosanguinea* 20004522, 'Red Bud', *M. turesii* T1-3-47, 'Snowdrift', 'Carmine', 'Makamik', and 'Sentinel' might be useful for pollination of 'Fuji'.

Cross compatibility. Pollen germination of commercial cultivars, 'Tsugaru' and 'Indo' was generally better than that of crabapples (Table 8). 'Snowdrift', 'Tsugaru' and 'Indo' had higher percentage of pollen germination than 'Peachleaf', *M. baccata* 79091 'May-

Table 8. Cross compatibility between 'Fuji' and ornamental crab apple cultivars in 2007-2008.

Cultivar or clone	Pollen germination %	Fruit set (%)	No. of seeds per fruit
M. baccata 79091	18.5 a	82.5	9.6 e
Peachleaf	19.7 ab[z]	78.2	8.3 cd
Nagasakizumi	29.0 abc	89.9	7.4 ab
Red Splendor	29.7 abc	95.0	7.5 abc
Maypole	30.5 abc	89.9	8.5 d
Sentinel	33.3 abc	92.5	7.3 a
M. × *atrosanguinea* 20004522	38.5 abcd	98.8	8.0 bcd
Red Bud	46.9 bcde	92.1	8.3 cd
Makamik	51.2 cde	96.3	8.1 bcd
Snowdrift	65.4 e	87.5	7.3 ab
Tsugaru	65.5 de	88.8	7.2 a
Indo	66.8 e	93.8	8.1 bcd
Significance[y]			
Cultivar	*	NS	**
Year	**	**	NS
Cultivar X Year	NS[x]	NS[x]	**

[z] Mean separation within columns by least significant difference (LSD) test at P=0.05

[y] NS, *,** = nonsignificant, P=0.05, P=0.01, respectively

[x] Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one-degree of freedom test.

pole', Nagasakizumi, and 'Sentinel'. The percentage of fruit set for all cross combinations between crabapples and 'Fuji' was more than 70% and the significant differences among cultivars were not found (Table 8). The crabapple cultivars are compatible as pollinizers for 'Fuji' as well as the other apple cultivars. Differences between cultivars with respect to the number of seeds depended on the year. However, *M. baccata* 79091 and 'Maypole' had higher number of seeds per fruit than 'Snowdrift', 'Tsugaru', Nagasakizumi, 'Sentinel', and 'Red Splendor'. Keulemans et al. (8) and Uemura et al. (14) found a positive correlation between fruit weight and the number of seeds. The difference between 7.9 and 9.3 seeds per fruit affected the fruit size significantly when comparing open pollination with hand pollination (14) .Since consumers in Japan prefer large and uniform apples, the number of seeds per fruit is an important factor for selecting crabapple pollinizers in Japan.

Pollen germination and fruit set on 'Tsugaru' did not differ significantly among cultivars (Table 9). The percentage of fruit set in all cross combinations between crabapples and 'Tsugaru' was more than 70%. 'Snowdrift' had higher number of seeds per fruit than the other cultivars. *M. baccata* 79091 had the lowest seed numbers per fruit. The lower percentage of pollen germination of this cultivar may affect the number of seeds per fruit.

Matsumoto et al. (9, 10) analyzed the *S*-RNase genotypes of several crabapples. The *S*-genotype of Shandingzi-1(*S4Sx*), *M. turesii* T1-3-47 (*S24S26*), 'Red Bud' (*S25Sx*), 'Snowdrift' (*S25Sx*), *M.* × *atrosanguinea* 20004522 (*S26Sx*), Nagasakizumi (*S26Sx*), 'Red Splendor' (*S26Sx*), and 'Sentinel' (*S26Sx*), 'Jack' (*SxSx*), and 'Profusion 91039 (*SxSx*) were identified. Most of the crabapple cultivars were thus fully compatible with Fuji *(S1S9)* and Tsugaru (*S3S7*). On the other hand, 'Peachleaf' (S1S5) and 'Makamik' ("*S1, 20,24like"Sx*) are semi-compatible with 'Fuji' in their S-RNase genotypes (9, 10). Partial S-allele incompatibility of pollinizers has been reported to affect the percentage of fruit set of apple cultivars (6). However, there was no difference in the percentage of fruit set between

Table 9. Cross compatility between 'Tsugaru' and ornamental crab apple cultivars (2007-2008).

Cultivar or clone	Pollen germination (%)	Fruit set (%)	No. of seeds per fruit
Red Bud	46.9	79.0	8.9 b[z]
Makamik	51.2	92.5	8.4 ab
*M. baccata*79091	18.5	93.4	7.9 a
M. × *atrosanguinea* 20004522	38.5	95.0	8.2 ab
Snowdrift	65.4	95.0	10.2 c
Maypole	30.5	96.9	8.2 ab
Sentinel	33.3	97.4	8.1 ab
Significance[y]			
Cultivar	NS	NS	**
Year	**	NS	*
Cultivar x Year	NS[x]	NS[x]	NS

[z] Mean separation within columns by least significant difference (LSD) test at P=0.05
[y] NS, *,** = nonsignificant, P=0.05, P=0.01, respectively
[x] Testing for interaction in two-way ANOVA method when there is only one observation per cell is given with Tukey's one-degree of freedom test.

fully compatible cultivars and semi-compatible cultivars in the present study. Further research is needed to determine if there is a difference in fruit set between fully compatible pollinizers and semi-compatible pollinizers of 'Fuji' and 'Tsugaru'.

Considering bloom period, flower intensity, regularity of flowering, and cross-compatibility between commercial cultivars and crabapples, the following cultivars are suggested as potential pollinizers for 'Fuji' and 'Tsugaru': *M. baccata* 79091 and 'Sentinel' for early bloom; *M.* × *atrosanguinea* 20004522, 'Red Bud' and 'Snowdrift' for mid-bloom. 'Snowdrift' was selected as a pollinizer for 'Delicious' on the basis of bee behavior and bloom timing in Washington (11). The bloom of 'Delicious' is 2 days later than 'Fuji' under our climatic conditions. 'Sentinel' coincided with the bloom period of 'Fuji' and 'Tsugaru'. However, 'Sentinel' tended to produce fewer seeds per fruit in artificial pollinations on 'Fuji' (Table 8). *M. baccata* 79091, *M.* X *atrosanguinea* 20004522, 'Red Bud' and 'Snowdrift' did not overlap the entire bloom period of 'Fuji' and 'Tsugaru'. This observation suggests that both early-blooming pollinizers and mid-blooming pollinizers should be planted at the same orchard.

'Makamik' showed high performance for flower intensity and cross-compatibility. Further research is needed to study the interaction between flower color and foraging behavior of horned-face bees.

Single-cultivar orchards have many advantages such as ease of management and avoiding spray drift. Even in small-scale orchards, apple growers can try the single-cultivar orchard with good profits. Additional research on the crabapple pollinizers we selected is needed to assess them for sensitivity to latent viruses, to compare rootstock effects on their growth and flowering, and to optimize their placement and spacing in the orchard.

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