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A model for representing the relationships among crop load, timing of thinning, flower bud formation, and fruit weight in apples

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ABSTRACT

The thinning of flowers or fruit is an essential practice for apple (*Malus* x *domestica* Borkh.) growers to achieve consistent production, and as many fruits as possible must grow to marketable size without biennial bearing to attain maximum economic value. Since almost no information is available to help determine when and how much to thin trees in each cultivar to obtain fruit of a certain size every year, we developed a theoretical model using 'Fuji' to explain the relationships among the timing of thinning, crop load, fruit weight, and bloom return. The rate of flower-bud formation in the current year could be explained by a regression model in which the timing of thinning, crop load, and rate of flower-bud formation in the previous year were used as variables. When trees are managed at the same timing and level of thinning every year avoiding biennial bearing, the rate of flower-bud formation is theoretically determined to be a certain value. The fruit weight in the current year could be explained by a regression model in which the timing of thinning, crop load, rate of flower-bud formation, and shoot length in the current year and the previous year were used as variables. Using the two regression models, we revealed that when 'Fuji' trees were managed so that the length of shoots was 30 cm, the fruit weight of the trees would be about 270 g in the case that the crop load was three fruits per cm^2 of trunk cross-sectional area (TCA), whereas it would be 180 g in the case that the crop load was six fruits per cm^2 TCA. When the trees were managed so that the length of the shoots was 40 cm, the fruit weight of the trees would be 50 g higher than that in trees with shoots 30 cm in length. On the other hand, when thinning was performed at 15 days after bloom, the fruit weight of the trees would be only 10–20 g higher than that in trees thinned at 30 days after bloom.

1. Introduction

The thinning of flowers or fruit is an essential practice for apple (*Malus* x *domestica* Borkh.) growers to achieve consistent production every year. Insufficiently thinned trees result in heavy cropping, which leads to small fruit and low bloom return. Intensively thinned trees result in light cropping, which often leads to large fruit and high bloom return but low yield because of reduced numbers of fruit (Wünsche and Ferguson, 2005). The timing of thinning also influences fruit size, and early thinning is effective for improving fruit size. Although the timing and severity of thinning could determine fruit size and yield in the current year and for several subsequent years (Byers, 2003), the influence of the timing of thinning and the crop load on flower-bud initiation has been unclear and remains difficult to predict (Dennis, 2000).

To attain maximum economic value, as many fruits as possible must grow to marketable size without biennial bearing. There have been many studies in which several timing variations and levels of thinning were set up as treatments, and the influence of the treatment on fruit size, yield, and bloom return was evaluated. Almost all of the studies demonstrated only that fruit weight and bloom return were improved by treatments in which early thinning was conducted and the crop load was light (Jones et al., 1992; McArtney et al., 1996; Byers and Carbaugh, 2002; Embree et al., 2007; Meland, 2009; Breen et al., 2015; Samuolienė et al., 2016; Serra et al., 2016). These studies did not indicate an optimum timing or level of thinning to produce fruit of a desired size. Stover et al. (2001) revealed the optimum crop load in several cultivars by assessing the relationships among crop load, fruit size, packinghouse prices, and costs for managing fruit. However, the study did not evaluate the influence of thinning on bloom return. Koike and Ono (1998) and Koike et al. (2003) recommended that primary thinning should be performed until 30 days after full bloom, leaving one fruit per 50–60 leaves, in order to harvest fruit above 300 g in the biennial cultivar 'Fuji.' The recommendation of these studies, however, was made based on observation for only two years. Biennial bearing is

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characterized by heavy blooming in the "on" year, which generally leads to an overset of fruit and reduced cropping in the "off" year, which in turn leads to significantly lower cropping (Greene, 2002), and the "on" and "off" years are alternately repeated. Therefore, it would be necessary to observe flower formation for at least three consecutive years to judge whether the trees are in a biennial cycle. Robinson (2008) concluded that crop load should be limited to six fruits per trunk cross-sectional area (TCA) in high-density orchards based on theoretical cumulative fruit production over six years.

Responses to thinning are likely to differ among cultivars and among trees grafted on different rootstocks. The use of appropriate dwarfing rootstock often increases the number of floral buds, but the effects are difficult to measure objectively unless the crop loading on trees with different rootstocks is uniform (Webster and Wertheim, 2003). Although recognizing the response of each cultivar and rootstock to thinning is extremely important for maximizing economic value (Stover et al., 2001), the genetic potential to initiate flower buds and to develop fruit under a certain level of crop load remains unclear in many cultivars and rootstocks because no conclusive evaluation method has been established. This means that growers cannot help relying on the standard practice of thinning, such as that fruit must be removed within the first three to four weeks after bloom (Dennis, 2003) even if there is a cultivar with the potential to initiate many flower buds and produce large fruit under heavy cropping despite late thinning.

The objectives of this study were to develop a theoretical model to explain the relationships among the timing of thinning, crop load, fruit weight, and bloom return and to propose the optimum timing for thinning and crop load to produce the most fruit within the target size range every year using the parameters of the model.

2. Materials and methods

2.1. Plant materials

The biennial cultivar 'Fuji' was used to develop a model for representing the response to thinning. Trees used were planted in orchards (39°3′N, 141°3′E, 190 m altitude) of the Division of Apple Research, Institute of Fruit Tree and Tea Science, NARO, Japan, and trained as slender spindles. No heading was done until the trees reached 4 m in height and no pruning was done except to remove branches that get too large during a few years after planting. The rootstocks and planting density of the trees are shown in Table 1. To produce large diversity in response to thinning, trees of several different ages were used, and the numbers of tree repetition were not adjusted. All trees were managed identically in accordance with standard orchard practice except for the timing and level of thinning. The timing of thinning was set for each tree and fixed during this study from 2012 to 2016 (Table 1). The timing of thinning at 0, 10, and 20 days after bloom was before physiological fruit drop (June drop). The level of thinning was changed among trees in which thinning was performed at the same time. Thinning was performed by hand as follows: All clusters of axillary buds were removed. Clusters of terminal buds were removed more or less according to the level of thinning established in advance, and flowers/fruitlets on each remaining cluster of terminal buds were thinned to one.

2.2. Measurement of variables

The timing of thinning (TT) was expressed as days after bloom. Crop load (CL) was expressed as number of fruits per cm^2 TCA. The TCA was calculated by measuring trunk circumference in the winter of the previous year at 20 cm above the grafting site. The rate of flower-bud formation (RF) was determined by counting flowering terminal buds per total terminal buds between 1.5 m and 2.5 m above the ground at flowering time. Shoot length (SL) was measured after leaf fall using five shoots selected evenly from around the tree between 1.5 m and 2.5 m above the ground. Fruit weight (FW) was calculated by dividing the yield of a tree by the number of fruits harvested.

2.3. Model for predicting RF

Since apple bearing is basically biennial, RF in the following year tends to be high and low when RF in the current year is low and high, respectively. The RF in the following year can be expressed as follows:

$$RF_{k+1} = 1 - RF_k \quad (1)$$

where RF_k and RF_{k+1} are the rate of flower-bud formation in the k^{th} and following year ($k+1$), respectively. The objective of thinning is to remove or reduce the influence of current excessive bloom on flower-bud formation in the following year. When thinning is performed most effectively, all of the terminal buds bear flowers in the following year ($RF_{k+1} = 1$). On the other hand, when there is no thinning effect, flower buds are formed according to the RF in the current year ($RF_{k+1} = 1 - RF_k$). This can be expressed by the following equation:

$$RF_{k+1} = 1 - (1 - E) \cdot RF_k \quad (2)$$

where E is the thinning effect. Most effective thinning ($E = 1$) results in $RF_{k+1} = 1$, and no thinning effect ($E = 0$) results in $RF_{k+1} = 1 - RF_k$. The thinning effect is assumed to be determined by the timing of thinning (TT) and level of thinning. The level of thinning is the same as CL (crop load). The maximum thinning effect means that all flowers are picked (CL = 0) at the time of bloom (TT = 0). Then the thinning effect can be expressed by the following equation:

$$E = (-\beta_1 \cdot TT + 1) \cdot (-\beta_2 \cdot CL + 1) \quad (3)$$

Table 1
Conditions of 'Fuji' trees used in this study, with the timing of thinning being set for each rootstock from 2012 to 2016.

Rootstock	Dwarfing class[z]	Tree age[y]			Tree spacing	Timing of thinning (n)[x]
JM5	Super dwarfing	1	–	5	1 m × 4 m	10(2), 20(2)
JM1	Dwarfing	1	–	5	1 m x 4 m	0(5), 10(5), 20(5), 30(5)
		6	–	8	1.5 m × 3.5 m	0(2), 20(3), 40(2)
		8	–	10	1.5 m × 3.5 m	0(2), 20(2), 40(2)
M.9	Dwarfing	1	–	5	1 m × 4 m	0(1), 10(1), 20(1)
		8	–	10	1.5 m × 3.5 m	0(2), 20(2), 40(1)
JM7	Dwarfing to semi-dwarfing	1	–	5	1 m × 4 m	0(5), 10(5), 20(5), 30(5)
		8	–	10	1.5 m × 3.5 m	0(2), 20(2), 40(2)
M.26	Semi-dwarfing	8	–	10	1.5 m × 3.5 m	0(2), 20(2), 40(2)
JM2	Semi-dwarfing to semi-invigorating	2	–	6	4 m × 4 m	0(3), 20(3)[w]
Marubakaido	Semi-invigorating	2	–	6	4 m × 4 m	0(2), 20(2)

[z]Refer to Iwanami et al. (2009) and Webster and Wertheim (2003).
[y]Expressed as the beginning and end of this study.
[x]Expressed as days after bloom and number of trees thinned at each timing every year.
[w]Three trees were thinned at 0-day after bloom every year except for one year when the three trees were thinned at 20-day after bloom.