WA 38 Flower Biology, Fruit Set, and Crop Load Management

(WA 38: Best Management Practices)

Abbreviations

1-MCP = 1-methylcyclopropene
ai = active ingredient
AVG = aminoethoxyvinylglycine
DM = dry matter
EB = early bloom
EPP = effective pollination period
FB = flower bud
GSI = gametophytic self-incompatibility
I_{AD} = index of absorbance difference
L:F = “leaf-to-fruit” ratio
LA:F = “leaf-area-to-fruit” ratio
LAI = leaf area index
PDF = preharvest fruit drop
PF = petal fall
PGRs = plant growth regulators
RM = reflective material
SDP = starch degradation pattern
SSC = soluble solids content
TA = titratable acidity
TCSA = trunk-cross-sectional area
WSEUP = Washington State Experimental Use Permit

Flower Biology and Fruit Set

Flower Biology

WA 38 usually blooms the third or fourth week of April in the Wenatchee and Yakima apple-growing areas of Washington but can bloom as late as the first week of May, depending on the weather. In some years and in some areas in Washington, it was observed that WA 38 bloomed a bit later and with a more gradual and prolonged bloom than other varieties, likely due to an occasional insufficient accumulation of chilling units during winter. The flower clusters, or inflorescences, generally consist of five or six flowers, but can occasionally consist of only four (Evans et al. 2012). WA 38 flowers exhibit the standard anatomy of apple blooms (five petals and five styles), with flowers at balloon stage showing white-pink petals that begin to lighten near anthesis and continue to pale until maturity and petal fall (Evans et al. 2012). The central, or apical, flower in each inflorescence is commonly known as the king and is surrounded by four or five lateral flowers, which are delayed in development (Figure 1) (Serra et al. 2022b). The variety shows a gradient in blooming between king flowers and the laterals (side blooms) with the phenology of the latter being delayed 48–72 hours with respect to the king. Under optimal environmental and pollination conditions, the king is the most likely flower to set to fruit (Serra et al. 2022b). The lateral blooms, which bloom later, serve as a backup strategy within the cluster because they still have a chance to get pollinated if the king encounters a detrimental fate. In years with spring weather conditions typical of the Washington State apple growing region (not extreme at bloom), anthesis of all flowers within a cluster occurs in a span of time ranging from five to eight days, and petal fall in as early as two days following king bloom. Petal fall can last from eight to ten days (Serra et al. 2022b).

The S-genotype of WA 38, which determines its compatibility or incompatibility with other apple cultivars, is S_5S_{24} (for further discussion, see section Suitable Pollinizers) (Sheick et al. 2020).

Effective Pollination Period (EPP)

One of the primary aspects linking flower biology and fruit set is the effective pollination period (EPP), which is defined as “the time period during which a pollination event is effective to produce fruit” (Williams 1965). The duration

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of the EPP (Figure 2) is determined by three biological processes: stigmatic receptivity, the length of time stigmas are receptive to pollen adhesion; pollen tube growth, the length of time required for the tubes of germinated pollen grains to travel down the styles toward the ovules and fertilize them; and ovule longevity, the length of time the ovules are receptive to fertilization before they lose viability.

Research has shown that WA 38 stigmas can support pollen adhesion and germination for about eight to nine days, while the viability of WA 38 ovules persists for about eight to ten days (Figure 2). Although pollen tube growth rates can differ depending on pollen source and quality, when Granny Smith pollen was used to determine EPP in WA 38 over two consecutive years, the effective pollination period for WA 38 ranged from approximately 1.4 to 3.2 days (Serra et al. 2022a). Thus, while the bloom window of WA 38 can persist for nearly two weeks (average bloom duration across three years is 12 days), each flower may have only a few days during its development in which pollination can lead to fertilization. It is important to note that the factors involved in calculating EPP are weather-dependent and can vary between years. For example, warm temperatures may hasten pollen tube growth while simultaneously accelerating ovule senescence, or loss of viability (Sanzol and Herrero 2001).

Figure 1. WA 38 flower cluster with the central king flower at anthesis and five lateral flowers with their characteristic phenological delay. Photo: S. Serra.

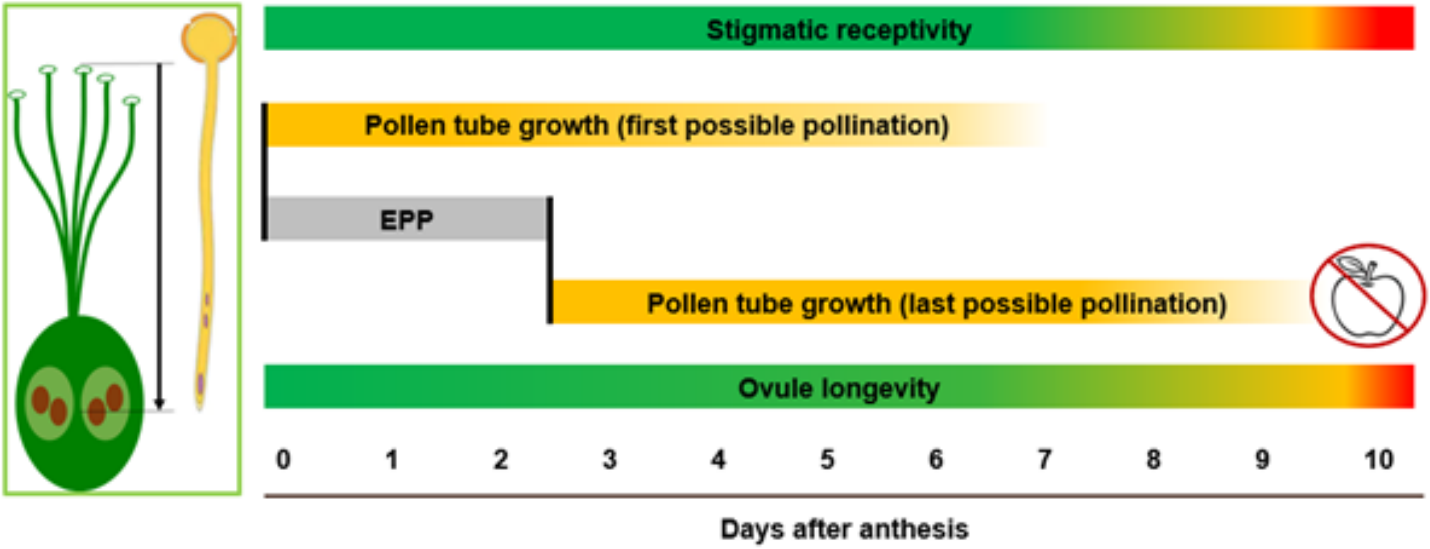

Figure 2. WA 38 effective pollination period (EPP) averaged 2.3 days across two consecutive years of study (Serra et al. 2022a). The EPP is determined by three main factors: duration of the receptivity of the stigma to pollen adhesion, the length of time required for pollen tubes to reach the ovule and fertilize the eggs, and the duration of ovule viability.

Key Points:

- WA 38 blooms in clusters with an early-blooming central king flower, usually surrounded by four or five lateral flowers reaching anthesis approximately two to three days after the king.
- In two consecutive years of research, the effective pollination period (EPP) in WA 38 flowers ranged from 1.4 to 3.2 days.
- Under favorable blooming conditions, the king flower is the most likely to set fruit; lateral flowers may also set at a lower frequency.

Suitable Pollinizers

Most cultivated apple varieties, including WA 38, require cross-pollination for satisfactory fruit set due to gametophytic self-incompatibility (GSI). The selection of a pollinizer variety should consider not only bloom timing and duration (Figure 3) but also genetic cross-compatibility. Cross-pollination can be achieved by planting (cross-) compatible varieties near WA 38 trees. Pollination is enhanced by supplying insect pollinators, usually honeybees (*Apis mellifera*); however, supplemental pollen applications have successfully facilitated pollination in WA 38 (see section Supplemental Pollen Spray and ReTain Application). Although domestic apple cultivars, such as Granny Smith, can effectively serve as pollinizers for WA 38, cross-compatible crabapples are also popular. Crabapples can offer several benefits over domestic apples (Crassweller et al. 1980; Johansen 1982), including profuse bloom (which correlates to pollen abundance), small fruit size, and the ability to plant them in-row with WA 38.

The GSI system in apple is a reproductive strategy that promotes genetic diversity, which can be advantageous for the success of the species in natural habitats but can be an inconvenient barrier to agricultural fruit production. Understanding whether a pollinizer variety is cross-compatible with WA 38 requires knowledge of the self-incompatibility genes carried by WA 38 and the pollinizer.

WA 38 is a diploid cultivar, meaning it carries two sets of genes: one from the paternal (pollen) parent and one from the maternal (egg) parent. Upon pollination, haploid pollen (carrying only one set of genes and, therefore, one S-allele) germinates on the stigmatic surface, and the emerging pollen tube elongates as it grows down the style and toward the ovary where the maternal (haploid) eggs reside. When the tube of a compatible pollen grain reaches an ovule, it deposits its genetic material into the ovule where it combines with the genetic material of the egg. This event is known as fertilization, and the resulting zygote, which may eventually become a seed upon fruit maturation, provides biochemical cues to promote growth and development of the fruit. When an incompatible pollen grain (i.e., one that carries an S-allele that is shared by the maternal cultivar) germinates on the stigmatic surface, pollen tube growth down the style is arrested before reaching the ovary. Insufficient fertilization can result in lower rates of fruit set. Thus, compatible pollinizer varieties must have S-alleles that differ from WA 38 to ensure pollen tubes can reach WA 38 ovules and stimulate fruit growth. Figure 4 outlines examples of incompatible (A), semi-compatible (B), and fully compatible (C) pollination scenarios in WA 38.

The S-genotype of WA 38 is S_5S_{24} (Sheick et al. 2020), which means any pollinizer variety carrying either the S_5 or S_{24} allele is semi-compatible, and any pollinizer variety with a genotype of S_5S_{24} is fully incompatible with WA 38 (Figure 4A).

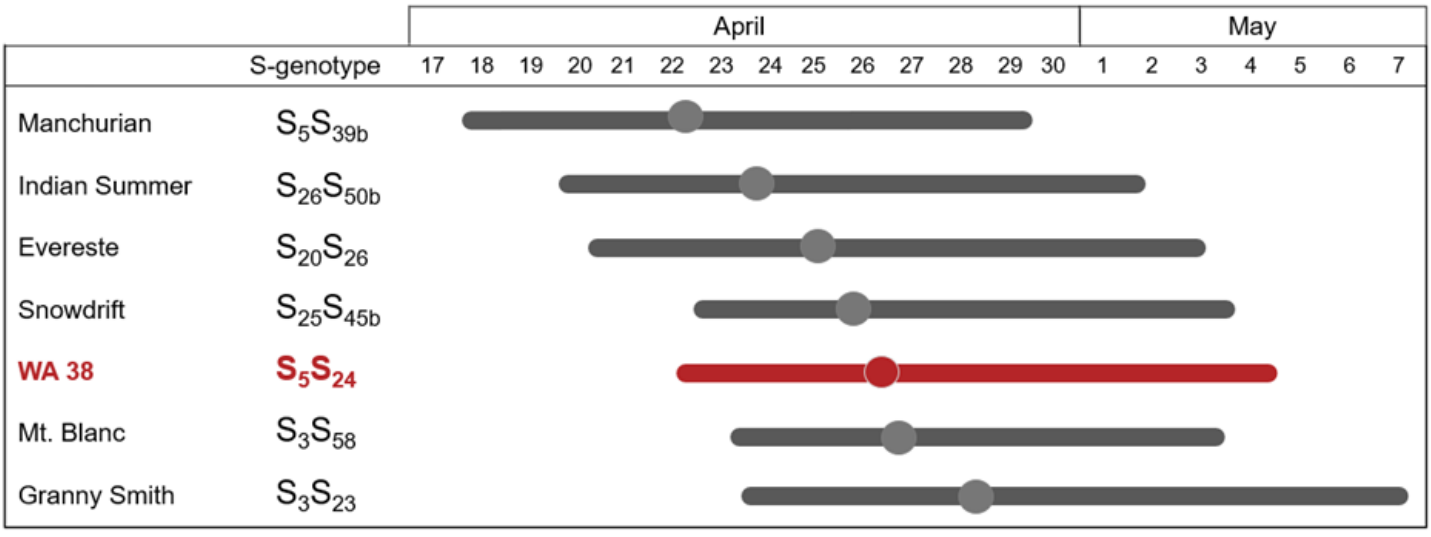

Figure 3. Bloom window with WA 38 included presented as an average of six years of bloom tracking from 2018 to 2023 in Rock Island, Washington. Each bar represents the duration of bloom for each pollen source from first bloom to end of bloom. The round markers indicate full bloom. Mt. Blanc is represented here as an average of five years of bloom data, while Granny Smith as an average of four years.

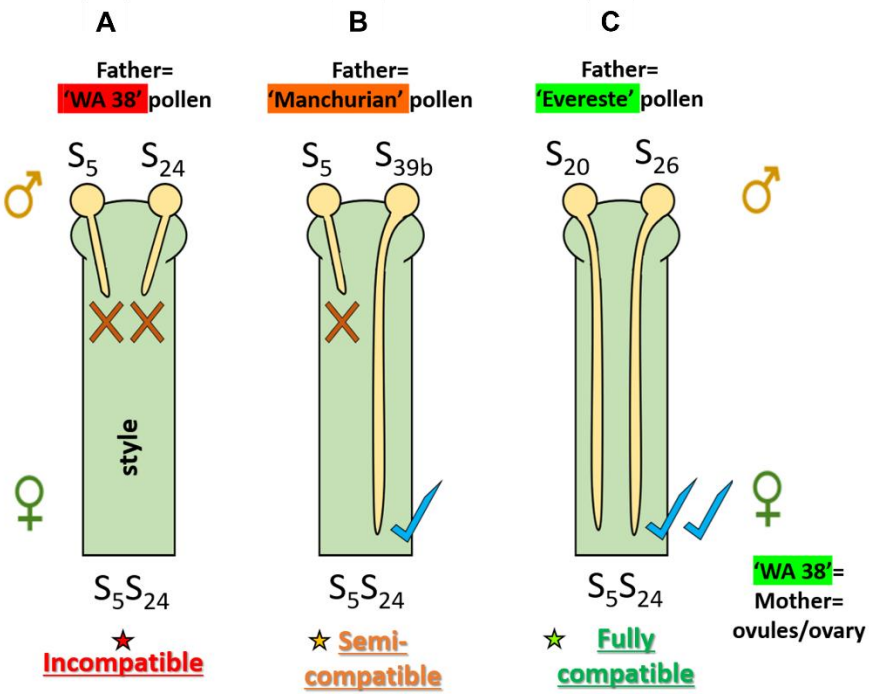

Figure 4. Examples of gametophytic self-incompatibility in WA 38 styles (♀, maternal side) with (A) fully incompatible WA 38 pollen (♂, paternal side), (B) semi-compatible Manchurian pollen (♂, paternal side), and (C) fully compatible Evereste pollen (♂, paternal side). Evereste represents an example of a fully compatible crabapple with WA 38; see Figure 3 for more examples. Pollinizers that carry either S_5 or S_{24} are semi-incompatible with WA 38, and pollinizers that carry both S_5 and S_{24} are fully incompatible with WA 38. Incompatible pollen is unable to fertilize WA 38 flowers; therefore, it is important to select compatible pollinizers to ensure satisfactory fertilization and fruit set. Modified from WSU Tree Fruit's *Cross-Compatibility of Apple Cultivars and Pollinizers* (Sheick et al. 2019) (https://treefruit.wsu.edu/article/cross-compatibility-of-apple-cultivars-and-pollinizers/).

Key Points:

- WA 38, like most apple cultivars, is self-incompatible and requires cross-pollination to achieve adequate fruit set.
- The genetic mechanism of self-incompatibility dictates that pollen grains carrying the same version of the self-incompatibility gene (S-allele) as the maternal parent will be unable to reach the ovules and fertilize the eggs successfully. Therefore, cross-compatibility must be ensured by selecting pollinizer varieties with S-alleles different from those of WA 38.
- Crabapples can be effective pollinizers for WA 38, but care must be taken to select cultivars with overlapping bloom windows (Figure 3), disease tolerance, and cross-compatible S-genotypes.
- WA 38 has an S-genotype of S_5S_{24}, so pollinizers like Frettingham ($S_{24}S_{25}$) and Manchurian crabapple (S_5S_{39b}) are only semi-compatible with WA 38, and thus only half of the pollen they produce can be used to fertilize WA 38 flowers (Figure 4B) (Sheick et al. 2018).
- Indian Summer, Evereste (Figure 4C), Snowdrift, and Mt. Blanc are fully compatible with WA 38, but their blooming tendencies and disease resistance traits may not be ideal for all orchards.
- Instead of relying on a single source of pollen, a variety of fully compatible crabapples or domesticated apples with overlapping bloom windows can be planted as pollinizers in WA 38 orchards to provide broader coverage of the bloom window to ensure satisfactory pollination year after year.

Fruit Set Management

Natural Drop Time and Intensity

Apple trees of most domestic cultivars often cannot support all fruitlets resulting from pollination during bloom until harvest. Fruits are a carbon sink for the tree, and only a finite number of apples can be supported depending on tree age and size. Apple trees regulate their reproductive load by prematurely shedding flowers and fruitlets across three main peaks of abscission. The first wave is known as the "cleaning drop" and occurs around petal fall when unfertilized flowers abscise. The second wave, commonly known as "June drop," involves the abscission of fruitlets during the cell division phase; the weakest fruitlets, characterized by declining growth rate, are shed. The third and final wave of shedding is known as "preharvest fruit drop" (PFD), which occurs in the days leading up to a cultivar's typical harvest window (Racskó et al. 2006; Serra et al. 2022b). In general, the fruitlet abscission in apple begins two to three weeks after petal fall (Dal Cin et al. 2009) and ends around five to six weeks after full bloom (Arseneault and Cline 2016), but the intensity of the drop is variety dependent. Some genotypes demonstrate a "self-thinning" tendency, meaning one apple per cluster persists after fruit set (Celton et al. 2014b). The mechanism behind the natural immature fruitlet drop is a complex aspect of fruit development that includes interactions between hormonal signaling (cortex and seeds), nutritional status,

growth rate, differentiation of abscission zone, and environmental conditions. In the case of WA 38, PFD does not contribute a significant proportion of natural drop; however, several years of data have shown this cultivar demonstrates significant self-thinning in the eight weeks following full bloom, extended beyond the traditional “June drop” and to a greater extent than most other cultivars (whose average abscission ends within six weeks after full bloom) (Arseneault and Cline 2016). The natural abscission observed in this variety has ranged between 83% (Figure 5) and 90% of fruitlets dropped in this time window, representing the sum of first and second waves.

For this reason, no chemical thinning is recommended at bloom, but in years when fruit set is high, a targeted hand thinning can be considered to improve the fruit size of overpopulated clusters (three or more apples per cluster) and promote return bloom. In an open pollination scenario, once the natural fruit shedding is complete, WA 38 showed that the majority of fruit were single within the cluster (51%), 12% were double, and a smaller proportion were triples. In some years, up to 38% of tracked flower clusters did not retain any fruit after the eight weeks of fruitlet abscission (Serra et al. 2022b). Because WA 38 does not present a significant PFD, early July (depending on the season and site) can be a suitable time to assess the expected crop load on a tree-by-tree basis for potential adjustment.

Key Points:

- WA 38 natural fruit abscission (drop) can last up to eight weeks after full bloom. After that time, no significant preharvest drop is observed.
- The majority of the crop sets one fruit per cluster. Two or three apples can also be set in a cluster, but these cases are observed at a lower frequency.
- In favorable pollination conditions at the time of king anthesis, the crop can result in over 60% of apples originating from king flowers. In contrast, in adverse pollination conditions (e.g., frost)—where king flowers are compromised or are otherwise unable to get pollinated—crop can set on lateral flowers anyway.

Growth Regulators and Fruit Set

Observations of intense fruitlet abscission and year-after-year crop fluctuations were common in WA 38 and led to the idea of evaluating potential horticultural tools to improve fruit set. One possible approach is using ReTain and Harvista, which disrupt ethylene signaling to extend ovule viability and decelerate floral senescence. These plant growth regulators (PGRs) might improve fruit set by improving the chances of successful pollination.

In one trial, early spring applications of aminoethoxyvinylglycine (AVG) (ReTain [Valent Bioscience, Inc.] applied as directed by the label) and 1-methylcyclopropene (1-MCP) (Harvista [Agrofresh Solutions, Inc]) applied in accordance with experimental permits #21008 and #22007 granted by Washington State Experimental Use Permit (WSEUP) (see disclaimer at the end of the article) were tested for their effectiveness in improving fruit set in WA 38 in a commercial orchard. PGRs were applied during early bloom (EB, 30%–50%) at king flower anthesis and at petal fall (PF). Treatments were applied at a rate of 50 g active ingredient (ai)/acre (or 1 pouch/acre) ReTain and 60 g ai/acre Harvista, as recommended by the manufacturers. The same treatments were repeated for two consecutive years over the same plots to evaluate the cumulative effect of treatment regimens at the end of the second year. At the end of the trial, the treatments applied did not impart differences in number of flower buds per tree or trunk-cross-sectional annual growth in relation to the untreated control trees. No relevant differences emerged in yield (kg per tree) at harvest in either trial year. However, the higher number of apples set in the ReTain EB treatment compared to the other four treatments in the second year resulted in meaningful variations in average fruit mass. The application of ReTain at the two phenological stages of bloom (EB and PF) led to a further increase in the crop load. The whole crop of the year was graded at a commercial packing line, and the results confirmed that because both the ReTain treatments increased the average number of fruits retained on trees until harvest, the proportions of graded apples belonging to the smallest size category (≤ 215 g or ≥ 88 apples/box) were the highest: 99.7% and 96.7% for ReTain EB and ReTain PF, respectively. The untreated control WA 38 performed better for size, with 14.6% of fruit belonging to the medium-size class (216–263 g or 80 apples/box). The proportions of medium-sized apples in both Harvista treatments were more comparable to those of the control group (Serra et al. 2022c). Color grading revealed ReTain EB produced the lowest proportion (78%) of apples in the Extra-Fancy and Fancy color grade, while 92% of control apples were scored as either Extra-Fancy or Fancy. The higher number of apples set in the ReTain EB penalized both the size and the development of superior overcolor due to the excessive competition between fruits.

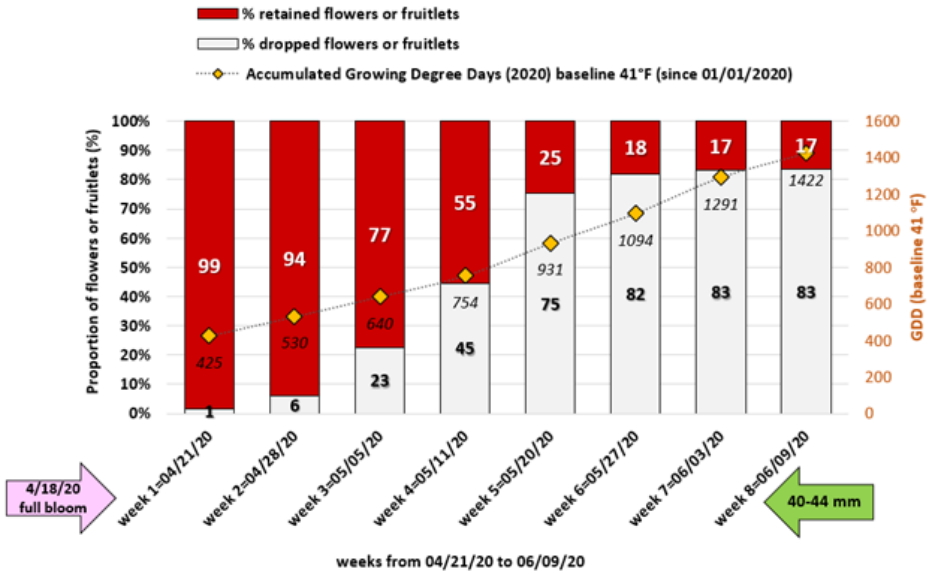

Figure 5. WA 38 natural green fruitlet abscission in 2020 (Rock Island, Washington) from the week of bloom (week 1) to week 8. The proportion (%) of flowers or fruitlets retained on tree are indicated in red, and the proportion of those dropped (%) is indicated in gray. One hundred clusters (=549 flowers) were tagged and monitored for this purpose. On the secondary Y-axis, the growing degree days accumulated are presented (41°F baseline = 5°C; start date for calculation 1/1/2020). The pink arrow reports the date of full bloom, and the green arrow shows the average range of retained fruit diameter at the end of the eight-week shedding. This figure was originally published in in *WA 38 Abscission and Fruit Development in an Open Pollination Scenario* (Serra et al. 2022b) (https://doi.org/10.17660/ActaHortic.2022.1346.17) and modified here.

Key Points:

- ReTain, when applied at early bloom (EB) or petal fall (PF), can result in higher crop loads per trunk-cross-sectional area (TCSA) in comparison to untreated WA 38 but does not increase the overall yield (kg per tree).
- The higher fruit numbers resulting from the ReTain treatment can be attributed to a greater proportion of fruit from clusters bearing multiple fruit, rather than an increase in flower bud formation.
- The increased fruit counts resulting from ReTain treatment were achieved at the expense of a lower average fruit mass and poorer coloration.
- Harvista, applied for experimental use (permit WSEUP # 21008 and # 22007) at either early bloom (EB) or petal fall (PF), was not effective in significantly improving yield (kg per tree), fruit size (average mass), or crop load (number of apples per tree).

Supplemental Pollen Spray and ReTain Application

Between 2020 and 2021, supplemental pollen application with or without ReTain was applied to evaluate their effects on fruit set and WA 38 productivity in multiple orchards. The supplemental pollen was applied at a rate of 30 g per acre and contained a mix of 70% Red Delicious and 30% Granny Smith pollen (Firman Pollen Inc., Yakima, Washington) suspended in a proprietary suspension media, except for one trial that applied dry pollen via dusting (no media). In all trials, except at the WSU Roza Experimental Farm (Prosser, Washington), the treatments were applied with a commercial electrostatic sprayer (OnTarget Spray Systems, Mt. Angel, Oregon). At the WSU Roza Experimental Farm, an electrostatic backpack sprayer was used for applications. The application rate varied between 30 and 50 gal/acre. The ReTain treatment consisted of 50 g ai/acre (or one pouch/acre) applied at bloom or petal fall (PF). In 2020, in a commercial WA 38 orchard near Buena, Washington, total fruitlets per tree varied between 60.4 ± 9.3 and 82.5 ± 9.3, being 36% higher with supplemental pollen spray treatment compared to the untreated control and ReTain. At harvest 2020, fruits per trees were 85%, 80%, and 48% higher in the ReTain, ReTain and pollen, and supplemental pollen treatments, respectively, compared with the control (Figure 6A). The following year, the trial was repeated in different rows, with two additional treatments: ReTain (PF) with or without a pollen application at bloom. Again, supplemental pollen, pollen and ReTain at bloom, and ReTain PF alone increased the number of fruit per tree by 66%, 59%, and 45%, respectively, when compared with the control (Figure 6B).

Similar results were observed at the WSU Roza Experimental Farm for WA 38 on M9-Nic29 rootstock, where fruit set was 74% higher with supplemental pollen application, followed by ReTain and ReTain and pollen spray. At harvest, yield per tree was 29% higher with ReTain and pollen compared to the control, while the other treatments were not different (Sallato and Khot 2024). The same treatments were imposed for WA 38 on G.41 rootstock, with no differences among treatments. However, the crop load (fruit number per trunk-cross-sectional area [TCSA]) was the lowest in the control (4.7 ± 0.7 fruit/cm^2 TCSA) and 25.5% higher in the supplemental pollen spray treatment (5.9 ± 0.7 fruit/cm^2 TCSA).

In two commercial fourth leaf WA 38 blocks, trials conducted in 2021 with the application of ReTain, supplemental pollen, or the combination of both resulted in no differences in fruit set or yield (Sallato and Khot 2024).

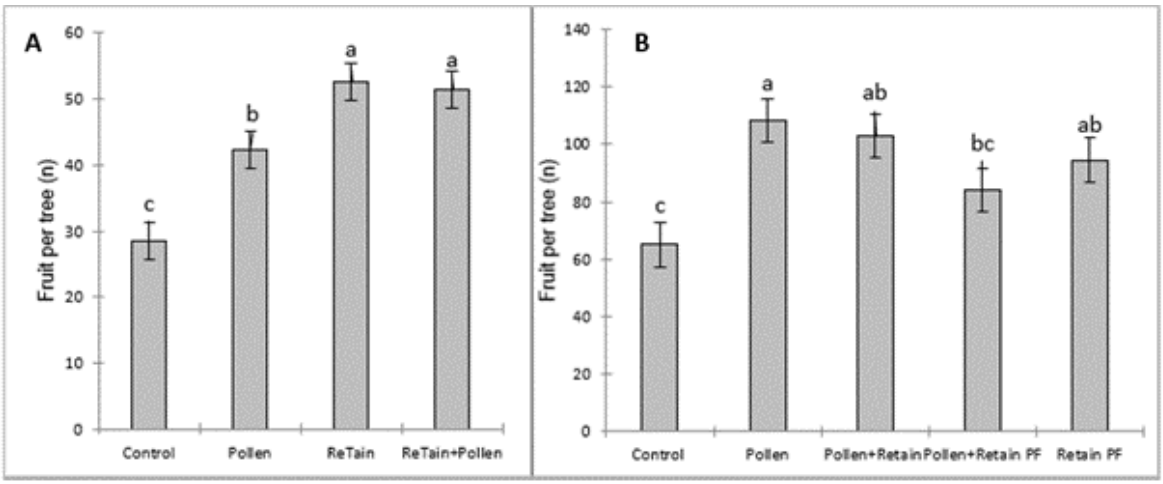

Figure 6. Total fruit (n) per tree at harvest in 2020 (A) and 2021 (B) at commercial WA 38 orchard near Buena, Washington. Treatments included an untreated control, pollen (at bloom), ReTain at bloom, ReTain and pollen, pollen and ReTain PF (at petal fall), and ReTain PF. Bars indicate mean values and error bars correspond to the standard error (n = 10). Different letters indicate significant differences between treatments ($p < 0.001$).

In a fifth trial conducted in Quincy, Washington, on a fifth leaf WA 38 orchard, the electrostatic application of pollen in a suspension media doubled the final fruit per tree when compared with dusted pollen. However, it was not different from the untreated control (Sallato and Khot 2024). Several Washington growers independently evaluated the use of pollen application via electrostatic sprayer or dusting. In a survey conducted among Washington apple growers regarding different orchard management strategies for WA 38, 11 out of 21 growers reported using supplemental pollen application during bloom, with six of them also using ReTain between bloom and petal fall. The use of ReTain at a later stage of fruit development has not been tested (Sallato and Khot 2024).

Key Points:

- Supplemental pollen aims to increase the availability and transfer of pollen to the open flowers; in WA 38 when applied at 30 g per acre in a suspension media by an electrostatic sprayer, fruit set and final fruit per tree increased in three out of six trials.
- The application of ReTain at bloom (targeting an increase in ovule longevity) or ReTain at bloom plus supplemental pollen increased the final fruit per tree in three out of five trials.
- The outcomes of supplemental pollen application and ReTain varied across the orchards, mainly due to variability in environmental conditions and site-specific characteristics.

Reflective Ground Cover

Reflective material (RM) is often deployed in the orchards two to seven weeks before harvest to improve the red coloration of some bicolor apple varieties, such as Honeycrisp, Fuji, and Gala (Iglesias and Alegre 2009; Hanrahan et al. 2011; de Sousa and Sánchez 2020).

WA 38 does not typically require supplemental preharvest tools like RM for marketable coloration but may benefit in other ways from additional diffuse light early in the season. Increasing the light availability in the orchard at an early bloom stage might improve carbon assimilation, reduce fruitlet competition, and facilitate flower bud formation for the following season (Wilkie et al. 2008).

To improve the fruit set in WA 38, reflective ground cover material (Extenday 80% diffuse reflection; Figure 7) was installed in the interrows at early bloom in a commercial orchard located at Royal City, Washington (fourth and fifth leaf), over two consecutive years and kept in place for one, two, or five months (Serra et al. 2024). The three RM duration treatments were compared against control (no RM). The retention of WA 38 fruitlets, assessed approximately every three weeks across two seasons, was not significantly improved in any of the RM treatments. Fruitlet drop in control trees (no RM) over the two years ranged within the expected percentage of abscission for WA 38. RM did not result in statistically significant increases in yield (kg per tree) or number of apples per tree. However, significant differences in the proportion of apples in the large size category emerged only in the 2022 season, with RM kept until harvest (five months) reporting the highest proportion of apples of that size (46.2%), while the no RM (control) the lowest proportion (25.7%). The other RM duration treatments did not show a clear trend for this parameter and the proportions of large apples were intermediate between RM until harvest and no RM (control) (Serra et al. 2024).

Figure 7. WA 38/Geneva935 orchard block trained as V-system and planted in 2018 (1,980 trees per acre) in Royal City, Washington. Orchard row on 4/28/2022, the day the reflective material (RM) was deployed (early bloom) (A), detail of most representative phenological stage of the flower cluster (king anthesis) the day of RM deployment (4/28/2022) (B), example of fruitlets dropped on the reflective material during the eight weeks of fruitlets abscission (C), and example of approximately eight-week-old apples (avg. 40 mm) retained on tree (D). Photos: S. Serra.

Key Points:

- RM deployed for various durations over the season did not significantly improve WA 38 photosynthesis, fruitlet retention, or yield compared to control (no RM) trees.
- The RM maintained until harvest had the effect of increasing the proportion of large apples, but these results were not consistent when RM was kept for the other time durations.

Effect of Pollinator Exclusion System on Fruit Set

For several years, in commercial and research orchards, WA 38 has shown satisfactory bloom and a self-thinning trait characterized by a post-bloom abscission window lasting eight weeks and a fruit drop intensity of up to 90% of the total fruitlets (Serra et al. 2022b, 2022a). Due to the significant natural drop of flowers and fruitlets in the weeks following bloom and the observation that approximately one-third of clusters can be unproductive at harvest, crop load following standard chemical thinning may be unpredictable and, therefore, is generally not a recommended approach to managing crop load for WA 38. Due to this variety's observed moderate alternate bearing (Anthony et al. 2020), any orchard practice that aims to achieve a more constant annual production and minimizes year-to-year fruit set swings merits investigation.

A pollinator exclusion system was previously tested in Honeycrisp in Washington and demonstrated that the use of netting as a physical barrier to restrict insect pollination at different flowering stages was successful in decreasing the fruit set when compared to an un-netted and un-thinned control (Elsysy et al. 2019). Although pollinator exclusion netting to restrict pollination would be too expensive and impractical for commodity cultivars that can crop regularly and have established thinning and crop load management strategies (e.g., Gala), this approach could be useful for higher value cultivars that are more difficult to manage by conventional approaches.

An exclusion netting trial was carried out at WSU Sunrise Research Orchard (Washington) for two consecutive years on WA 38/M.9-Nic29 (also known as RN 29) as a potential route to target the desired number of apples per tree (target fruit set) for a constant annual production without further thinning approaches. The netted treatment was compared to an un-netted, un-thinned control (natural fruit set). Mono-row drape nets (10% shading, 2.8 mm × 4.0 mm, Helios anti-hail systems, Bergamo, Italy) were deployed each year at early bloom stage in 2022 (in netted treatment; Figure 8A–C). The nets were kept closed to restrict bee pollination for four to five weeks depending on the season (Figure 8B), then opened until harvest at the end of September in both years.

Based on the first two years of data, the results confirmed that a physical barrier to pollination limited the number of pollinated flowers that resulted in fruit set compared to the un-netted control. Moreover, netting at bloom shortened the duration of the eight-week-long natural abscission period in comparison to the un-netted control. Since the net enclosure allowed only a fraction of king flowers to be pollinated, lateral flowers were left unpollinated and, therefore, did not compete for resources after bloom, reducing competition between fruitlets. The netting approach did not penalize the productivity per tree in both years; differences in yield between treatments were not significant. A significant difference in average apple mass was found in both seasons, with netted apples heavier on average than un-netted apples. The possible explanation for the reduction of smaller apples when adopting the exclusion netting deployed at bloom resides in preventing the fertilization of flowers on lateral clusters of one-year-old wood (ramo misto—i.e., one-year-old shoot bearing on lateral flower buds and on apical flower bud) that are usually delayed by several days in comparison to clusters on spurs or brindilla tips. This approach favors the fertilization of king flowers that are naturally more dominant and stronger inside the flower cluster with respect to laterals (Celton et al. 2014a).

The return bloom of the netted trees in the early spring of the second season was five times higher than that of the un-netted trees, while differences in the average number of flower buds (FB) per tree were no longer significant in the following spring.

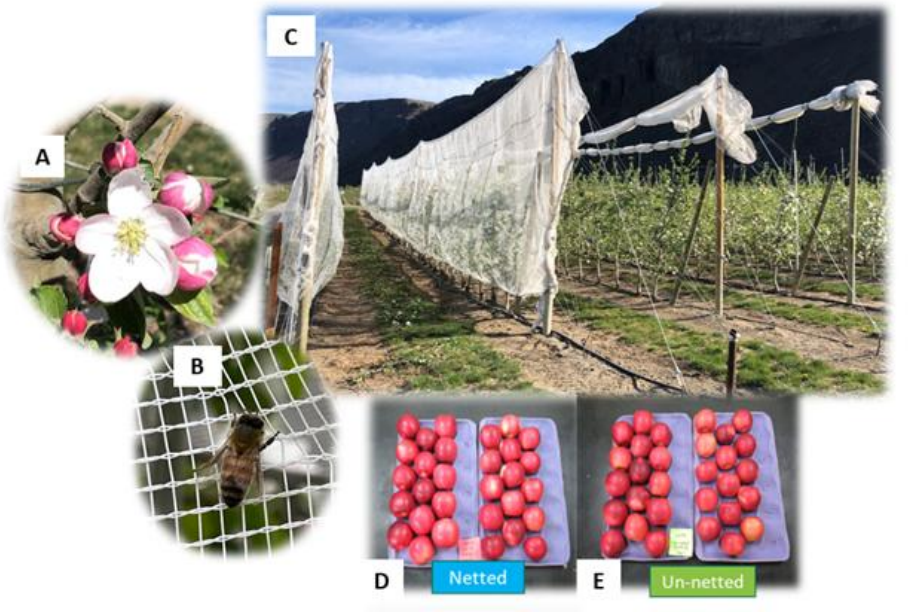

Figure 8. WA 38/M.9-Nic29 orchard block trained as spindle and planted in 2013 (1,489 trees/acre) in Rock Island, Washington. Detail of king anthesis (A); honeybee pollinator attempting to enter the net, the mesh dimensions do not allow pollination (B); orchard rows showing the two treatments: netted at early bloom and un-netted at bloom (C); example of apples from the netted treatment (D); and example of apples from the un-netted treatment (E). Both D and E apples were evaluated for quality, selected from Extra-Fancy and Fancy grade (50% to 100% red overcolor) and medium and large size (80 to 64 apples/40 lb box) categories in 2021. Photos: S. Serra.

This approach is still under investigation in WSU research plots but might be a suitable orchard practice for targeting a desired crop load and controlling biennial bearing while avoiding conventional chemical thinning techniques in WA 38. Because netting at bloom acts as a physical barrier to pollination, it is also a suitable approach in organic production systems.

Key Points:

- The adoption of pollinator exclusion netting at early bloom for up to five weeks reduced the number of fertilized flowers and abbreviated the natural abscission duration in comparison to the un-netted control.
- Netted treatment promoted the reduction of the proportion of small-sized apples, which are often the result of lateral flowers in one-year-old shoots and delayed blooms.
- Mono-row pollinator exclusion netting can be used to manage crop load in high-value blocks, avoid conventional thinning practices, and limit biennial bearing; therefore, it could be a sustainable approach for organic production.

Effect of Crop Load on Biennial Bearing and Fruit Quality

Alternate bearing is a tree fruit production concept known since the 1930s. Hoblyn and colleagues described year-after-year fluctuations in crop production in some of the orchards at the East Malling Research Station (UK) in 1936. They laid out three observed scenarios in this regard: trees regularly bearing every year, trees bearing irregularly, and others precisely bearing in a biennial manner (following a cyclic alternation between a year on with a high crop and a year off with a low crop). Monselise and Goldschmidt (1982) reported that cultivars prone to alternate bearing begin showing this cyclic tendency when a climatic event triggers it (e.g., frost or drought). Biennial bearing is very well known in the Washington industry, especially for Honeycrisp, which clearly shows this tendency despite not being a self-thinning variety. Therefore, an accurate thinning program is necessary to manage the crop year by year. WA 38 has shown signs of biennial bearing since fourth leaf in a pilot research block planted in 2013; the average number of flower buds per tree was counted for three consecutive years, reporting a year on in 2015 and 2017 and a year off in 2016. Moreover, the biennial bearing index calculated on fruit count per tree between years (as the absolute value of the difference in number of apples in two consecutive years divided by the sum of the produced apples in those two years) was higher in “bending” pruning technique (long pruning associated with bending of the branches ≥ 90 degrees in the first years after planting) in contrast to much less biennial tendency for WA 38 managed with “click” pruning (i.e., cutting the one-year-old shoot tips to promote basal bud break and blind wood mitigation) (Anthony et al. 2020).

Crop load management becomes essential to avoid irregular annual production and achieve a regular bearing year after year. With WA 38, managing fruit set is even more challenging than in other varieties because the self-thinning trait adds an additional layer of uncertainty to the predicted final crop. In a study conducted at WSU Sunrise Research Orchard (Washington), target crop loads from 2.1 to 7.8 apples/cm^2 TCSA were imposed on WA 38/M.9-Nic29 trained to a spindle in the third and fourth leaf for those trees, and many findings emerged (Anthony et al.

2019). Crop load was positively correlated with productivity, but this trend accompanied severe negative impacts on apple quality, with significant depletion in soluble solids content (SSC), dry matter (DM), titratable acidity (TA), and a delay in fruit maturity (Table 1). Apples picked from the four crop load levels were significantly different in their maturity a few days after harvest based on the DA meter non-destructive assessment (I_{AD}) (Ziosi et al. 2008). As expected, the higher the crop load level, the more unripe the apples were (Figure 9). The starch degradation pattern (SDP 1–6 or starch index, Hanrahan and Schuhmann, 2018) assessed on the same apples did not report significant differences across crop load levels, suggesting that the DA meter is more sensitive in distinguishing maturity differences than the starch index.

No significant differences emerged in the proportion of red overcolor, which was above 94% for all crop load treatments. Apple firmness was higher in lower crop load apples (2.1 fruit/cm^2 TCSA) than the 6.0 and 7.1 fruit/cm^2 TCSA treatments. The comparison between the highest and the lowest crop load in this trial showed a significant difference in SSC (1.41 °Brix) with no clear discrimination between 4.1, 6.0, and 7.1 fruit/cm^2 (Anthony et al. 2019). On the other hand, differences in DM were more apparent with increasing crop load than SSC; average DM of apples from the 7.8 fruit/cm^2 TCSA crop load treatment was 14.39%, while DM in the 2.1 fruit/cm^2 apples was 16.02% (Table 1).

Based on a previous study on consumer preference of WA 38 apples, medium (80 mm diameter) and large (85–95 mm) apples with dry matter content ranging between 14.00% and 16.99% DM were preferred by consumers in comparison to 17.00% to 18.99% DM apples (Musacchi et al. 2020). A similar impact of crop load on apple quality was found in a study on Honeycrisp conducted in Washington State; SSC and DM decreased with an increase of crop load from 3.3 apples/cm^2 to 9.4 apples/cm^2 (Baldassi et al. 2023).

The only significant results of the impact of crop load levels on WA 38 vegetative parameters were found in "leaf-area-to-fruit" ratio (LA:F) and "leaf-to-fruit" ratio (L:F) and not in total leaf area per tree, total number of leaves per tree, leaf area index (LAI), average leaf area, or annual trunk growth (Anthony et al. 2019). Trees with the lowest crop load (2.1 fruit/cm^2 TCSA) reported the highest LA:F ratio, significantly different from the other three crop load levels and 3.4 times higher than the 7.8 fruit/cm^2 (Anthony et al. 2019). L:F ratio better discriminated between the crop loads, with the highest ratio (48) for the lowest crop load and the lowest ratio (15) for the highest crop load; the other two intermediate loads were statistically similar (27 and 19). This means that at lower crop loads, more leaves are available for each cropped apple than at the highest crop load (Anthony et al. 2019).

The return bloom assessment carried out in this trial revealed that the lowest crop load showed a biennial tendency in comparison to the other three higher crop load levels (Anthony et al. 2019).

Key Points:

- High crop load (7.8 fruit/cm^2 TCSA) negatively affected WA 38 fruit quality, with lower maturity, soluble solid content, and dry matter percentage.
- Low crop load (2.1 fruit/cm^2 TCSA) showed severe fluctuations in flower bud formation year after year, indicating a biennial tendency if the crop load is not optimized.
- Accounting for apple quality, maturity vegetative traits, and return bloom, the ideal crop load for a five-year-old orchard of WA 38 was six fruit/cm^2 TCSA. This level might be adjusted when the blocks mature (five to ten years).

Table 1. The effects of four levels of crop load (from 2.1 to 7.8 fruit/cm^2 TCSA) on fruit quality and maturity (according to I_{AD}) immediately after harvest for WA 38 apples grown in Washington State's Wenatchee area in 2017. Apple quality analysis parameters were assessed on 80–90 mm fruit.

Crop Load (no. fruit/cm^2 TCSA)	Avg. Apple Weight (g)	I_{AD} (DA meter)	Red Overcolor (%)	Firmness (N)	SSC (°Brix)	Dry Matter (%)	Starch Degradation Pattern (SDP) (1–6)	Titratable Acidity (Malic acid %)
2.1	302 A	0.45 D	96.2	88.9 A	14.59 A	16.02 A	1.77	0.80 A
4.1	282 B	0.60 C	96.5	86.7 B	13.40 B	15.33 B	1.56	0.54 B
6.0	282 B	0.78 B	94.6	80.7 C	13.29 B	14.50 C	1.66	0.54 B
7.8	277 B	0.93 A	95.6	80.9 C	13.18 B	14.39 C	1.55	0.56 B
Significance	***	***	NS	***	***	*	NS	**

Source: Modified from Anthony et al. (2019).
Notes: NS = No significance; * $p < .05$; ** $p < .01$; *** $p < .001$

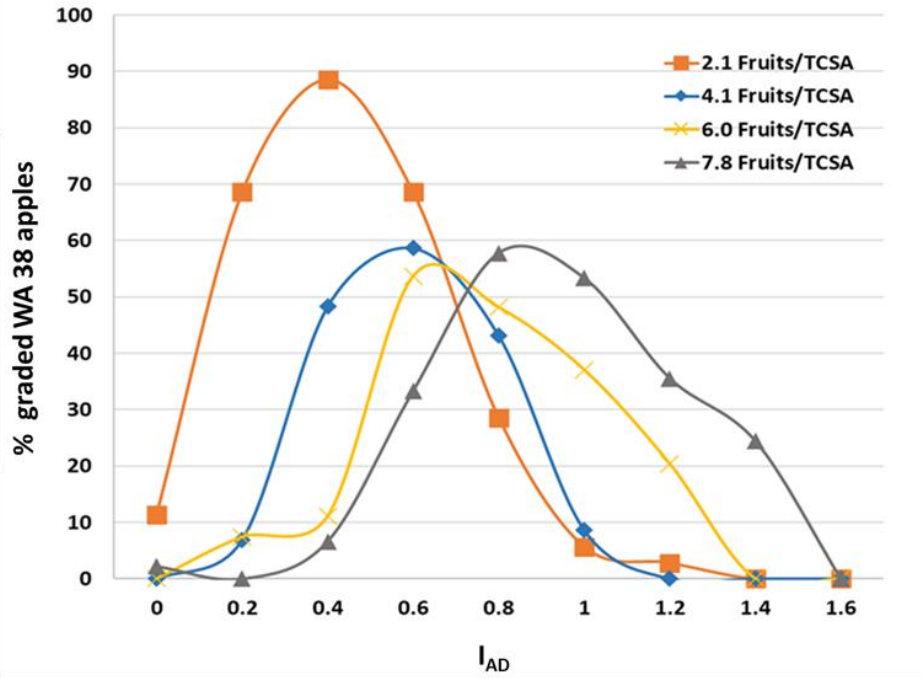

Figure 9. Index of absorbance difference (I_{AD}), proxy for chlorophyll content, measured on WA 38 apples by four crop load treatments after harvest in 2017 (no storage). Modified from *Optimizing Crop Load for New Apple Cultivar: "WA38"* (https://doi.org/10.3390/agronomy9020107) (Anthony et al. 2019).

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