Summer Mechanical Hedging to Prune Eight Cider Apple Cultivars

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SUMMARY. **Mechanical hedging was evaluated at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2019 and 2020 on eight cider apple (*Malus ×domestica*) cultivars with four bearing habits: tip—Golden Russet, Harrison; spur—Brown Snout, Cap of Liberty; semispur—Tom Putt, Campfield; and crab—Puget Spice, Hewe's Virginia Crab. Trees were planted on 'Geneva 935' (*Malus hybrid*) rootstock in one replicate block in 2014 and the second replicate block in 2016 and the central leader of all trees was headed in 2017 to equalize tree size and stage of development. Summer hedging was carried out on all cultivars on 16 July in 2019 and 7 July in 2020. The response of different cultivars was evaluated both years by measuring canopy area removed, shoot biomass removed, and fruit removed, and the amount of time to hedge was measured. Additionally, fruit diameter and fruit yield per tree were measured at harvest both years, and fruit weight was measured at harvest only in 2020. The hedger traveled at an average speed of 1.32 mph; it took 6 seconds on average to hedge both sides of one tree when in-row spacing was 6 ft and took 1.25 minutes to maneuver around the end of a row. The estimated time to hedge 1 acre was 1.45 hours when the hedger traveled at 116 ft/min and the orchard had 10 rows spaced 12 ft apart. Biomass removed on an area and weight basis was less in 2020 than in 2019, whereas yield per tree was 2.6 times greater in 2020 than 2019, and cultivars within a bearing habit differed in these responses to hedging both years. Fruit damaged by the hedger was assessed but observed to be negligible for all cultivars. Yield per tree was negatively correlated with fruit diameter ($P < 0.001$) and positively correlated with the number of fruit removed per tree ($P < 0.025$). Further research is needed to assess the long-term effects of hedging on biomass removal, yield, and biennialism to determine whether summer mechanical hedging is a cost-effective and suitable method for managing cider apple orchards.**

Cider apples (*Malus ×domestica*) are an emerging crop in the United States, and cider apple orchard management generally follows the same guidelines as that for dessert apples (Fitzgerald et al., 2013; Moulton et al., 2010). Pruning is commonly done by hand and can represent ≈20% to 25% of labor costs or 10% of annual operating costs in a cider apple orchard (Galinato et al., 2014). Limited access to workers with pruning experience in addition to rising wages can create a financial barrier for cider apple orchard establishment and maintenance (Clark, 2017; Moulton and King, 2015; Roper, 2005; Whiting et al., 2015). Pruning consists of heading cuts that remove a portion of a branch and stimulate growth and thinning cuts that remove the entire branch and improve canopy structure (Craig and Embree, 2006; Forshey, 1976). Mechanical hedging is a form of nonselective heading pruning that can reduce summer pruning costs as fewer employees can prune an orchard in less time than for hand pruning. The cost to hand prune a cider orchard in full production is ≈$1260/acre, and the cost of a hedger ranges from about $10,000 to $18,000 (Galinato et al., 2014, 2022). The hedger is mounted on a tractor and consists of a vertical cutter bar or discs and may also include an additional horizontal blade that simultaneously tops the trees (Sansavini, 1978). Hedging removes lateral growth from trees at a set distance from the trunk, creating a uniform "fruiting wall" in a plane perpendicular to the row floor or at a slight angle forming a conical canopy (Masseron, 2002; Sansavini, 1978; Sazo and Robinson, 2013).

The use of hedging was first documented in apple orchards in Italy in the 1960s and 1970s, was refined in the early 2000s, and today is used to create a fruiting wall canopy in modern tree fruit orchards throughout Europe (Masseron, 2002; Sansavini, 1978; Sazo and Robinson, 2013). Hedging is commonly performed in orchards that are planted medium- to high-density using dwarfing rootstocks and slender spindle architecture training systems (Sazo and Robinson, 2013). When mechanical hedging was first introduced, it was mainly carried out when trees were dormant and resulted in undesirable vigorous growth and reduced fruit size (Mika, 1986; Wertheim, 1978). Emerson and Hayden (1984) found that when summer hedging was compared with dormant pruning and dormant hedging, summer

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Units To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.6093	mph	$km \cdot h^{-1}$	0.6214
28.3495	oz	g	0.0353

hedging did not result in vigorous growth and yield was maintained for 'Jonathon', 'Ryan Red Delicious', and 'Golden Delicious' apples grafted onto M.7 rootstock, although fruit size was not evaluated. The same study concluded that summer hedging provided a reduction in labor expense and improved fruit color. Ferree and Rhodus (1993) found that summer mechanical hedging reduced spread, volume, and trunk cross sectional area of apple trees grafted onto M.7 and M.9 rootstock compared with standard pruning. Rootstock and consequently tree size are important considerations when interpreting the effect of the timing and severity of pruning, and less vigorous semidwarfing (M.7) and dwarfing (M.9) rootstocks likely respond less than standard rootstocks such as M.106 and M.111 (Sansavini, 1978; Saure, 1987). Other studies found that for trees that are grafted on dwarfing rootstock and trained to a slender spindle, summer hedging in conjunction with supplemental winter hand pruning can produce the ideal tree size without undesirable physiological tree responses (Mika et al., 2016; Sazo and Robinson, 2013). Hedging carried out in the summer, when fruit are increasing in size, encourages trees to set terminal buds and push bud growth behind the hedging cuts (Lewis, 2018; Saure, 1987). The removal of assimilates by summer hedging reduces their reserves, which reduces shoot regrowth the following season, thereby reducing tree vigor and pruning needs (Forshey, 1976; Mika 1986; Saure, 1987). However, hedging too early in the summer can result in too much shoot regrowth, whereas hedging too late in the season can also encourage vegetative growth at the expense of fruit quality and delay hardening (Flore, 1992; Forshey, 1976; Saure, 1987). Sazo and Robinson (2013) found hedging 'Fuji', 'Golden Delicious', 'Jonagold', and 'Gala' apples in June and July in New York resulted in short shoot regrowth (5 to 8 inches) with terminal buds; shoot growth was less with July hedging, and there was no shoot regrowth in August hedging. This suggested that July was the ideal time to achieve the goal of summer hedging with the least regrowth. Further, in that study, hedging took 5% of the time that was needed to perform manual pruning. Shoot growth was also reduced relative to a winter hand-pruned control for 'Gala' apple that were mechanically hedged in June and July in a study conducted over 4 years (Biddlecombe and Dalton, 2018).

Supplemental winter hand pruning is needed regardless of the timing of hedging to remove branches that extend along the row, for internal canopy thinning, to maintain crop load, and for dessert apples to achieve optimal fruit size (Ferree and Short, 1972; Sansavini, 1978). Whiting et al. (2015) found mechanical pruning in apple and sweet cherry (*Prunus avium*) to be 23 times more efficient than hand pruning, and hedging resulted in half as much biomass removal due to the lack of thinning cuts. In that study, summer mechanical hedging combined with dormant hand pruning was still significantly faster than hand pruning alone in both apple and sweet cherry (Whiting et al., 2015).

Hedging develops a tree architecture that leads to increased light interception and distribution, increased efficacy of agricultural chemical applications due to better coverage, and increased harvest efficiency due to increased visibility of fruit (Sazo and Robinson, 2013; Whiting et al., 2015; Zhang et al., 2017). Increased photosynthetic activity and carbohydrate production in leaves results in increased fruit quality for dessert apples, such as improved color, fruit size, and total soluble solids (Forshey, 1976; Heinicke, 1975; Lakso and Robinson, 2014; Saure, 1987; Wunsche et al., 1996). Mika et al. (2016) found that 'Pinova' apple trees mechanically hedged during the summer, in the first week of May or the first week of June, had higher yields than manually pruned trees, although fruit size was reduced in both cases. A reduction in fruit size shown in some studies (e.g., Ferree and Rhodus, 1993; Mika et al., 2016) was potentially due to fruit crowding because there were no subsequent thinning cuts. Fruit yield can also be impacted by hedging when some fruit are shaken from limbs due to the hedging motion, and some fruit will be cut by the blade (Sansavini, 1978; Sazo and Robinson, 2013). Hand pruning a fruiting wall would remove the same fruit bearing branches but would not shake fruit off the tree. Whiting et al. (2015) found that mechanical hedging during the summer had minimal impact on yield of 'Fuji' apple, and an average of 0.4 fruit were damaged per tree. Sazo and Robinson (2013) found that on average 8.5 and 3.8 fruit were removed per tree due to early- and late-season summer hedging, respectively, for fully grown trees of 'Fuji', 'Golden Delicious', 'Jonagold', and 'Gala' apples. Ferree and Rhodus (1993) found a reduction in fruit size from hedging but no impact on biennialism over 10 years of hedging spur-bearing 'Smoothee Golden Delicious', 'Empire', and 'Redchief Delicious' apples.

Summer hedging could significantly reduce pruning labor needs and costs in cider apples; however, there are several questions that must be addressed. First, popular cider apple cultivars have tip bearing (e.g., Golden Russet, Frequin Rouge) or spur bearing (e.g., Brown Snout, Cap of Liberty) habits, and it is unknown whether hedging impacts crop load and subsequent yield and fruit size differently for these bearing habits. Second, the research on fruit quality has primarily focused on dessert apple cultivars, and the impact on total weight per fruit and fruit size needs to be assessed in cider apple cultivars. This study addresses the need for more information regarding the impact of summer hedging on vegetative growth and fruit yield and quality of several popular cider apple cultivars. The hypotheses of the study are that the effects of summer mechanical pruning will differ based on cultivar and bearing habit, and that hedging will be a time efficient method for pruning. The goal of this research is to provide growers with orchard management recommendations that maintain fruit productivity and quality while reducing the amount of time for pruning.

Materials and methods

Study site and cultivar selection. This experiment was carried out in 2019 and 2020 at Washington State University's Northwestern Washington Research and Extension Center, Mount Vernon, WA, in a cider apple research orchard. The orchard contained 65 cultivars on 'Geneva 935' (*Malus hybrid*) rootstock with two replicates of three trees per plot arranged in a randomized complete block design. One replicate block was established in 2014 and the second replicate block was established in 2016 due to low supply of the rootstock, and the central leader were of all trees were headed to the same height in 2017 to equalize tree size and stage of development. Rows were 256 ft long, trees were spaced 6 ft in-row and 12 ft between rows, planting density was 605 trees/acre, and the orchard block was 0.85 acre. Trees were trained to a slender spindle architecture, with 10-ft posts spaced 36 ft apart, and a four-wire trellis with the irrigation drip line on the lowest wire.

Eight cultivars were selected for this study: Brown Snout, Campfield, Cap of Liberty, Golden Russet, Harrison, Hewe's Virginia Crab, Puget Spice, and Tom Putt. Cultivars were representative of four bearing habits, tip, spur, semispur, and crab and of early-, mid- and late-season harvest times (Miles and King, 2019). According to historical data at this site, cultivar Cap of Liberty has a strong tendency toward biennialism, Harrison, Brown Snout, and Campfield are classified as semibiennial, and Puget Spice, Golden Russet, Tom Putt, and Hewe's Virginia Crab are classified as consistent bearing (Miles and King, 2019).

Hedging. Mechanical hedging was carried out across the whole orchard with a tractor-mounted single sickle bar mower-hedger (Phil Brown Welding, Conklin, MI) on 16 July in 2019 and on 7 July in 2020. The tractor traveled at 1.27 mph in 2019 and 1.37 mph in 2020, with the hedger aligned 2 ft from the main leader and set in the center hole of the mount. Both years, the time to hedge one side of each row was recorded (10 rows, 256 ft each) and the average time to hedge both sides of a single 100-ft row was calculated. Concurrently, the time to hedge the entire orchard was measured and the average time to maneuver around the end of a row was calculated. The amount of time to hedge a 1-acre orchard was then calculated to provide a comparison for commercial scale orchards using the following formulas that depend on row spacing, tractor speed, and the number of rows.

$$43,560\ \text{ft}^2(1\ \text{acre}) \div \text{V feet (between–row spacing)}$$
$$= \text{W feet (orchard row feet)}$$
$$[\text{W row feet} \div \text{X feet per minute (tractor speed)}]$$
$$\times 2\ (\text{two passes per row}) = \text{Y minutes}$$
$$\text{Y minutes} + \{\text{Z minutes (turn–around time)}$$
$$\times [(\text{n} \times 2) - 1]\},$$

where n is the number of rows minus one as the tractor does not turn around after the last row.

Cultivar response. The impact of hedging on canopy removal was assessed using digital images and a computer application to measure green canopy cover (Canopeo ver 2.0; Canopeo, Stillwater, OK) developed in the programming and computing environment MATLAB (Mathworks, Natick, MA) (Patrignani and Ochsner, 2015) and by weighing pruned branches. Data were compared between both measurement methods to determine if digital imaging was an effective assessment of pruning biomass removal. For the digital image method, one photograph per plot was taken on each side of the row before and after hedging. Photographs both years were taken 8 ft from the center tree in each plot with a digital camera zoomed all the way out. A white poster board 36 inches wide by 44 inches tall was positioned 18 inches away from the center tree in each plot to provide a backdrop and reference points for the images. The position of the poster board was marked on the ground using flags in each plot for consistency. The before and after hedging images were cropped to the size of the poster board and the software calculated canopy cover by analyzing the percentage of pixels in each image that met the selection criteria, which were specified ratios of red/green and blue/green. The difference between pre- and post-pruning images was calculated as percent canopy removal on an area basis. For the pruning weight method, branches extending 12 inches from the center of the row into the drive alley were painted for traceability before hedging, with paint color alternated between plots in each row. Pruned material was weighed directly after hedging.

Fruit removal. The number of fruit removed by hedging was estimated in 2019 by counting the number of fruit on one representative branch of the center tree in each plot pre- and post-hedging. Total fruit per tree was estimated by multiplying the number of fruit per branch by the number of fruit-laden branches per tree. In 2020, the number of fruit removed by hedging was counted and weighed for all trees per plot.

Harvest and fruit quality. Apples were harvested in 2019 when a random sample of four fruit, one from each canopy quadrant of the center tree in each plot, reached a minimum average Starch Pattern Iodine index value of five (scale is one to eight where eight indicates no starch present in the cortex and the fruit is fully mature) (Blanpied and Silsby, 1992). In 2020, apples were harvested when a random sample of four fruit from each canopy quadrant of the center tree in each plot had a rating 7 to 8 on the 8-point Starch Pattern Iodine Index. Harvest was later in 2020, when fruit reached full maturity, as this is more desirable for cider. Both years the two plots per cultivar were harvested by hand on the same day, and fruit weight was recorded per plot. One representative tote (≈14 kg) was assembled and weighed per plot by collecting an equal number of fruit from all harvested totes. Fruit in the representative tote for each plot were sorted for damage and fruit that were rotted, lacerated, or bruised from the hedging blade were weighed separately and percent of fruit in each category was calculated. Lacerations were defined as cuts on the apple that were 1 cm or larger, and bruises were counted if they were dark (indicating they were not fresh), larger than 3 cm in diameter, and irregular in shape. Rotted fruit were discarded, and all other fruit were recombined in the representative tote. Both years, 25 fruit were randomly selected from the tote, average fruit diameter was measured, and in 2020 average fruit weight was also calculated; fruit weight was not measured in 2019. Total yield for each plot was compared each year to determine if there was an impact of consecutive years of hedging on biennial fruit production of the cultivars in this study, and if there was a difference between tip and spur bearing cultivars.

Data analysis. Data were analyzed using analysis of variance (ANOVA) carried out in R (version 1.2.5033; R Studio, Boston, MA). Linear mixed effects models were used with cultivar and year or bearing and year as fixed effects and block as a random effect using the "nlme" package (Pinheiro et al., 2020). Interactions were tested and significance was reported at $\alpha = 0.05$. Where the ANOVA indicated a significant difference of the main or simple effects, a post-hoc means separation was carried out using Tukey's honestly significant difference with the "lsmeans" command in the "emmeans" package (Lenth, 2020). Assumptions of homogeneity of variance and normality were tested using a Levene's test and a Shapiro-Wilk test, respectively. Heterogeneity of variance between cultivars and bearing habits were accounted for using the command "weights = varIdent" from the "nlme" package (Pinheiro et al., 2020). Where the ANOVA indicated an interaction between cultivar or bearing habit and year, years were analyzed separately due to heterogeneity of variance between years. Where normality assumptions were not met, data were transformed by square root as appropriate and the assumptions were then satisfied; however, in all cases, transformed data gave the same conclusions as the original data, and thus the original data are presented to aid interpretation. The relationships between fruit diameter and weight, fruit diameter and yield, and fruit weight and yield were analyzed with simple linear regression.

Results

Hedging efficiency. It took 2.3 min to hedge one side of one row (256 ft) in 2019 and 2.1 min in 2020. Average time to hedge both sides of a 100 ft row was ≈1.7 min. At the planting density of this orchard (605 trees/acre), it took on average 6 s to hedge both sides of one tree. Average time to maneuver around the end of a row was 1.25 min. Thus, at the row spacing, average tractor speed, and number of rows in this study, the time to hedge 1 acre would be ≈1.45 h. Supplemental winter pruning in this study took ≈4 min per tree; however, the employees were unskilled at pruning, and there were differences in tree canopy structure among cultivars that prevented a consistent pruning routine.

Year differences. There were significant differences ($P < 0.0001$) between 2019 and 2020 in biomass removed by hedging (measured both as percent area and by weight), number of fruit removed by hedging, fruit diameter, and yield per tree for the eight cider apple cultivars in this study (Table 1). There was more biomass removed in 2019 than in 2020, 26.4% and 0.7% on an area basis and 0.44 and 0.16 kg on a weight basis, respectively, and there was a positive correlation between the two biomass removal measurements ($R^2 = 0.39$; $P < 0.001$). The number of fruit removed was 1.5 times greater and yield per tree was 2.6 times greater in 2020 than 2019. Fruit diameter was 13% smaller in 2020 than in 2019. There was a negative correlation between yield per tree and fruit diameter ($R^2 = 0.32$; $P < 0.001$); that is, as yield per tree increased, fruit diameter decreased. The number of fruit removed per tree by hedging was negatively correlated with fruit diameter ($R^2 = 0.17$; $P < 0.025$) and positively correlated with yield ($R^2 = 0.16$; $P < 0.025$). That is, as yield per tree increased the number of fruit removed by hedging per tree increased and fruit diameter decreased. There was no correlation between weight per fruit and yield or weight per fruit and the number of fruit removed per tree.

Bearing habit differences. When analyzed by bearing habit, there were minor interactions between bearing habit and year in the number of fruit removed per tree by hedging and yield per tree ($P \leq 0.01$; Table 1); however, these differences were largely due to a few cultivars. There were no bearing habit by year interactions for biomass removed on an area or weight basis or for fruit diameter ($P > 0.10$). Percent canopy removed and pruning weight did not differ among diff-

Table 1. Biomass removed by hedging measured as canopy area and weight, number of fruit removed by hedging, average fruit diameter, weight per fruit in 2020, and yield per tree at harvest for eight cider apple cultivars and four cider apple bearing habits in 2019 and 2020 treated with mechanical hedging at the 19- and 12-leaf stage, respectively.

Treatment	Area removed (%)[z]	Biomass removed (kg)[y]	Fruit removed (no.)[x]	Fruit diam (cm)[w]	2020 fruit wt (g/fruit)[v]	Yield (kg/tree)[u]
	Mean ± SE					
Year						
2019	26.4 ± 4.6	0.44 ± 0.07	14 ± 5	5.7 ± 0.10	NA	4.76 ± 0.76
2020	0.7 ± 0.8	0.16 ± 0.07	35 ± 5	5.0 ± 0.08	66.4 ± 1.7	17.24 ± 1.44
P value	<0.0001	<0.0001	<0.0001	<0.0001	NA	<0.0001
Bearing						
Crab	11.0 ± 5.2 NS	0.26 ± 0.11 NS	36 ± 4 a[t]	4.1 ± 0.07 c	11.1 ± 1.3 c	16.87 ± 0.78 b
Semispur	6.2 ± 2.5	0.34 ± 0.10	10 ± 3 b	7.0 ± 0.11 a	100.5 ± 6.1 a	9.24 ± 0.48 c
Spur	9.0 ± 2.1	0.24 ± 0.11	32 ± 10 ab	5.2 ± 0.11 b	45.2 ± 3.4 b	3.35 ± 0.96 d
Tip	6.1 ± 3.0	0.36 ± 0.16	7 ± 4 b	5.5 ± 0.70 b	110.5 ± 2.1 a	21.32 ± 0.91 a
P value	0.277	0.412	<0.0001	<0.0001	<0.0001	<0.0001
P value (bearing × year)	0.184	0.446	0.010	0.138	NA	<0.0001

[z]Biomass removed measured as percent area of the canopy profile removed per plot.
[y]Biomass removed by weight per tree; 1 kg = 2.2046 lb.
[x]Number of fruit removed per tree.
[w]Fruit diameter calculated as the average of 25 random fruit calculated postharvest both years; 1 cm = 0.3937 inch.
[v]Fruit weight calculated as the average 25 random fruit collected postharvest in 2020; 1 g = 0.0353 oz.
[u]Yield per tree calculated as yield per plot divided by three trees per plot.
[t]Means with different letters within columns are significantly different according to Tukey's honestly significant difference test at α = 0.05; NA = not applicable, NS = not significant.

erent bearing habits (P = 0.28 and P = 0.41, respectively; Table 1). Percent canopy removed ranged between 6% (tip-bearing cultivars) and 11% (crab cultivars), whereas pruning weight ranged between 0.24 kg per plot (spur-bearing cultivars) and 0.36 kg per plot (tip-bearing cultivars). Crab-bearing cultivars had the most fruit removed by hedging (36 fruit per tree), and semispur- and tip-bearing cultivars had the least number of fruit removed (eight fruit per tree); spur-bearing cultivars were intermediate ($P < 0.001$). Crab-bearing cultivars had the smallest fruit (4.1 cm) and the lightest fruit (11.1 g in 2020) and semispur cultivars had the largest fruit (7.0 cm) and the heaviest along with tip-bearing cultivars (average 105.5 g in 2020), whereas spur-bearing cultivars were intermediate ($P < 0.001$ for diameter both years and weight per fruit in 2020). Tipbearing cultivars had the highest yield per tree (21.32 kg), and spur-bearing cultivars had the lowest (3.35 kg) ($P < 0.001$).

Cultivar differences. Biomass removed on an area basis and on a weight basis, the number of fruit removed per tree by hedging, fruit diameter and weight, and yield per tree all differed significantly by cultivar, and there was an interaction between cultivar and year for biomass removed by weight and yield per tree. Data presented in Table 2 is the mean for both years. 'Cap of Liberty' had less biomass removed on an area basis (9%) compared with 'Harrison' (11.5%), and all other cultivars were similar to each other (9% on average). The amount of biomass removed on a weight basis was highest for 'Harrison' (0.61 kg) and lowest for 'Golden Russet' and 'Puget Spice' (0.12 kg). 'Hewe's Virginia Crab' had the most fruit removed by hedging per tree (37) and 'Campfield', 'Golden Russet', and 'Tom Putt' had the fewest (average 10 fruit per tree). 'Campfield', 'Golden Russet', and 'Tom Putt' had the largest fruit (average 6.8 cm) and the heaviest fruit (average 110 g in 2020), whereas 'Puget Spice' had the smallest (3.1 cm) and the lightest fruit along with 'Cap of Liberty' (average 26.5 g in 2020). 'Harrison' had the greatest yield per tree (21.46 kg), whereas 'Brown Snout', 'Campfield', 'Cap of Liberty', and 'Golden Russet' had the lowest (average 4.86 kg per tree).

Weight of biomass removed per tree was greater for each individual cultivar in 2019 than 2020 (Table 3). 'Harrison' had among the most biomass removed per tree (0.96 kg) in 2019, and 'Hewe's Virginia Crab' had the most (0.32 kg) in 2020. 'Golden Russet' and 'Puget Spice' had the least biomass removed on a weight basis in 2019 (0.17 kg on average) and 'Golden Russet' had the least in 2020 (0.08 kg). 'Campfield' had the lowest yield per tree in 2019 (0.81 kg), and 'Cap of Liberty' had the lowest in 2020 (6.12 kg), 'Harrison' had the highest both years (12.66 and 32.57 kg, respectively) along with 'Hewe's Virginia Crab' and 'Puget Spice' in 2020 (33.81 and 28.98 kg, respectively).

Discussion and conclusions

The cider apple orchard in this study was hedged for the first time in July 2019 and for a second time in July 2020. Hedging speed was 0.11 mph (0.177 $km \cdot h^{-1}$) slower in 2019 than in 2020 because it took longer in 2019 to cut wood that was several years old, whereas in 2020 wood that was cut was current-year growth. This difference in the age and thus size of the wood that was removed was reflected in the weight of biomass removed, which was almost 2 times greater overall in 2019 than 2020. The proficiency of the tractor driver for hedging may have also increased over time. In subsequent years, it is likely that the hedger will move as fast or faster as in the second year of hedging, 1.37 mph (2.205 $km \cdot h^{-1}$). The orchard training system, topography, tree age, and planting density can also affect the speed the hedger is able to travel (Sansavini, 1978). For example, Whiting et al. (2015) reported that in a 'Fuji'/'Nic 29' orchard with

Table 2. Biomass removed by hedging measured as canopy area and weight, number of fruit removed by hedging, average fruit diameter, weight per fruit in 2020, and yield per tree at harvest for eight cider apple cultivars and four cider apple bearing habits in 2019 and 2020 treated with mechanical hedging at the 19- and 12-leaf stage, respectively.

Cultivar	Bearing	Area removed (%)[z]	Biomass removed (kg)[y]	Fruit removed (no.)[x]	Fruit diam (cm)[w]	2020 fruit wt (g/fruit)[v]	Yield (kg/tree)[u]
		Mean ± SE					
Hewe's Virginia Crab	Crab	16.4 ± 7.7 ab[t]	0.40 ± 0.10 ab	37 ± 5 a	4.1 ± 0.07 c	28.1 ± 4.2 d	16.77 ± 0.76 bc
Puget Spice	Crab	5.0 ± 5.2 ab	0.12 ± 0.08 c	30 ± 20 ab	3.1 ± 0.06 d	11.1 ± 1.3 e	23.20 ± 3.86 ab
Campfield	Semispur	5.0 ± 2.5 ab	0.35 ± 0.11 abc	9 ± 2 b	7.0 ± 0.37 a	100.5 ± 6.1 ab	5.03 ± 0.83 e
Tom Putt	Semispur	10.8 ± 6.0 ab	0.33 ± 0.08 ab	17 ± 1 b	7.0 ± 0.12 a	118.8 ± 0.1 a	9.37 ± 0.49 d
Brown Snout	Spur	13.6 ± 2.7 ab	0.16 ± 0.08 bc	48 ± 18 ab	5.2 ± 0.17 b	45.5 ± 2.5 d	5.19 ± 2.73 cde
Cap of Liberty	Spur	8.9 ± 1.9 b	0.31 ± 0.13 abc	25 ± 12 ab	5.1 ± 0.27 b	41.9 ± 9.5 cde	2.80 ± 1.07 e
Golden Russet	Tip	4.3 ± 2.9 ab	0.12 ± 0.07 c	6 ± 3 b	6.4 ± 0.11 a	110.7 ± 2.1 a	6.43 ± 2.72 bcc
Harrison	Tip	11.5 ± 2.1 a	0.61 ± 0.09 a	25 ± 12 ab	5.5 ± 0.07 b	74.9 ± 4.9 bc	21.46 ± 0.91 a
P value		<0.0001	<0.0001	0.005	<0.0001	<0.0001	<0.0001
P value (cultivar × year)		0.238	0.013	0.419	0.304	NA	0.0003

[z]Biomass removed measured as percent area of the canopy profile removed per plot.
[y]Biomass removed by weight per tree; 1 kg = 2.2046 lb.
[x]Number of fruit removed per tree.
[w]Fruit diameter calculated as the average of 25 random fruit calculated postharvest both years; 1 cm = 0.3937 inch.
[v]Fruit weight calculated as the average of 25 random fruit collected postharvest in 2020; 1 g = 0.0353 oz.
[u]Yield per tree calculated as yield per plot divided by three trees per plot.
[t]Means with different letters within columns are significantly different according to Tukey's honestly significant difference test at α = 0.05; NA = not applicable.

Table 3. Weight of biomass removed by hedging and yield per tree for eight cider apple cultivars and four cider apple bearing habits in 2019 and 2020 treated with mechanical hedging at the 19- and 12-leaf stage, respectively.

		Biomass removed (kg)[z]		Yield (kg/tree)[y]	
		2019	2020	2019	2020
Cultivar	Bearing	Mean ± SE			
Hewe's Virginia Crab	Crab	0.48 ± 0.13 ab[x]	0.32 ± 0.04 a	5.64 ± 1.62 bc	33.81 ± 1.86 a
Puget Spice	Crab	0.17 ± 0.11 c	0.07 ± 0.04 bc	18.06 ± 5.05 ab	28.98 ± 3.06 a
Campfield	Semispur	0.54 ± 0.17 abc	0.17 ± 0.09 abc	0.81 ± 0.42 d	12.86 ± 1.17 b
Tom Putt	Semispur	0.53 ± 0.16 abc	0.14 ± 0.03 b	5.01 ± 1.13 bc	15.09 ± 1.23 b
Brown Snout	Spur	0.24 ± 0.12 bc	0.08 ± 0.03 bc	1.77 ± 2.69 abcd	10.42 ± 1.28 bc
Cap of Liberty	Spur	0.49 ± 0.21 abc	0.13 ± 0.05 abc	0.77 ± 0.84 cd	6.12 ± 0.61 c
Golden Russet	Tip	0.16 ± 0.11 c	0.08 ± 0.03 c	3.74 ± 2.65 abcd	9.84 ± 6.03 abc
Harrison	Tip	0.95 ± 0.16 a	0.26 ± 0.09 abc	12.66 ± 1.32 a	32.57 ± 0.76 a
P value		0.001	0.002	<0.0001	<0.0001

[z]Biomass removed by weight per tree; 1 kg = 2.2046 lb.

[y]Yield per tree calculated as yield per plot divided by three trees per plot.

[x]Means with different letters within columns are significantly different according to Tukey's honestly significant difference test at $\alpha = 0.05$.

3700 trees/ha with similar topography and training system as in the current study, the hedger traveled at 1.8 km·h^{-1}, which was 6 s per tree. The planting density in the current study was 1495 trees/ha, the hedger moved 0.4 km·h^{-1} faster than in the aforementioned study, and it also took 6 s to hedge each tree. Thus, time to hedge per tree is dependent on planting density as well as driving speed, driver proficiency, and age of the biomass being removed. Supplemental dormant pruning in the current study took 4 min per tree, which is a considerable amount of time for hand pruning compared with a higher density two-dimensional canopy. The cultivars in this study differed from each other in tree canopy structure, and this prevented a consistent pruning routine. Further, the employees in the current study were unskilled at pruning, and this was the primary factor that resulted in increased time for hand pruning. In a single cultivar orchard and with skilled labor, the time to carry out supplemental winter pruning would likely be substantially less than in the current study. Although speed of hedging and hand pruning will vary for each orchard, the time to hedge is considerably less than for hand pruning (Sazo and Robinson, 2013). Furthermore, a single-sided sickle bar mechanical hedger like the one used in this study is a relatively low-cost technology ($10,000; Phil Brown Welding, Conklin, WI) and only requires one person (tractor driver) to complete the majority of pruning activities in an orchard. Thus, mechanical hedging appears to be an affordable technology for orchards of all scales.

The biomass removed by hedging as measured on an area basis was only different for two of the eight cultivars in this study; however, the weight of biomass removed with hedging differed for more cultivars. This result indicates that the weight measure of biomass removal is more sensitive for showing differences among treatments. Further, there was a significant correlation between the two measurements to assess biomass removal, and it was faster to measure biomass removal by weighing removed biomass; thus, weight of removed biomass appears to be a better measure of the effect of hedging on the tree canopy.

If considered alone, the relationship between the number of fruit removed by hedging and yield per tree could suggest that the removal of fruit from hedging resulted in higher yield per tree. However, the correlations between the number of fruit removed by hedging, fruit diameter, and yield per tree more likely show that more fruit small fruit resulted in higher yields. Although trees with high numbers of small fruit lost a greater number of fruit due to hedging, the percentage of fruit removed was small relative to their total crop load. Further, the crab cultivars Puget Spice and Hewe's Virginia Crab, which were two of the highest yielding cultivars, were not observed to set fruit on 1-year-old wood, and so hedging did not cut off fruit-bearing wood. On the basis of these results, all that can be inferred is that it is unlikely that removing fruit by hedging results in reduced yield, and further studies are needed to elucidate the potential relationship between hedging, fruit size and number, and yield.

The bearing habit initial designation for each cultivar in this study was taken from historic observations of these cultivars on other rootstocks at this site (Miles and King, 2019). To ascertain whether these designations were correct, the ratio of tip- to spur-borne apples on branches of the eight cultivars in this study was assessed in 2021 by counting the bearing sites of each tree and noting the location on the branch. Although two of the cultivars were bearing few fruit, we observed almost all of the noncrab cultivars to have greater than 50% spur-borne apples. However, an overall low crop load for these cultivars in 2021 may affect this ratio. Of the four cultivars that were designated as semispur or tip-bearing based on the historical record, only 'Golden Russet' fit its historical categorization as tip-bearing. It is not known whether this result is because of a redistribution of fruit bearing sites due to hedging because we did not collect data on bearing sites in 2019 or 2020. Ultimately, findings from this study suggest that cultivar plays a greater role than growth habit in response to hedging, and response may differ for cultivars within a bearing habit.

Significant differences between years, especially in yield, may be due to several factors. First, the trees responded to being hedged for the first time; second, the trees in the orchard were relatively young the first time they were hedged and were still in the growth maturation stage—all trees were essentially at the fifth leaf stage as they were pruned to the same size 2 years before the study commenced; and third, a natural biennial alternation may have occurred with the cultivars. Many popular cider apple cultivars are prone to biennial bearing (e.g., Lambrook Pippin, Yarlington Mill), and it is unknown whether summer hedging exacerbates or mitigates biennial bearing in these cultivars when they are grafted on modern dwarfing rootstocks. A longer-term study such as by Ferree and Rhodus (1993) would be ideal to further explore this question. Compared with 2019, 2020 was likely an "on" year with higher return bloom and fruit set than the year before. However, although yield increased for all cultivars in 2020, the percentage of fruit removed was consistent both years, indicating a similar response to hedging. Despite the potential effects of biennialism, and the cultivar-by-year interaction for several parameters, all data measured for cultivars in this study showed similar trends both years. The correlation between yield per tree and fruit diameter indicates that higher crop load can result in smaller fruit (Racskó, 2006). Because cider fruit are not sold based on size, smaller fruit do not have a negative impact on cider apple marketability.

A final concern with hedging is the damage that occurs to branches from rough cuts, where branches split or fray, could serve as infection sites for disease. This damage was observed both years after hedging in this study but was not extensive. In western Washington where this study was carried out, apple anthracnose canker (caused by *Neofabraea malicorticis*) can reduce tree vigor and kill young or small trees (Garton et al., 2018). The orchard in this study was managed following general practices for the region that included a spray rotation of protectant and systemic fungicides applied every 3 weeks throughout the growing season to prevent fungal disease (Garton et al., 2018; Moulton et al., 2010). The trees were closely monitored for disease, which was observed to be minimal throughout the study orchard and was not observed at all in the cultivars evaluated for this study. Further, overall disease incidence and severity appeared to be the same as in the adjacent cider apple orchard blocks that were not hedged. In other regions, fire blight (caused by *Erwinia amylovora*) is a primary concern (Smith et al., 2019). Hedging occurs later in the season, after the infection period of this disease, and thus it is unlikely that hedging would cause an increase in infection.

In summary, the time for one person to hedge 1 acre was ≈1.45 h, which can conserve time and labor for pruning. For the eight cultivars that were hedged in this study, fruit yield differed by cultivar but was not negatively affected by biomass removed on a weight basis or the number of fruit removed by hedging. Further research is needed to determine the long-term effects of hedging on biomass removal, fruit yield, and biennialism for cider apple cultivars. The possibility that heading cuts from mechanical hedging can alter the bearing habit of cider apple cultivars should be explored because this could affect decisions regarding pruning and training. A fungicide application program suitable for the region can control the risk of disease from rough hedging cuts.

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