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CONVERSION OF TALL SPINDLE ‘BRAK FUJI’ APPLE TREES TO A NARROW TREE WALL WITH HEDGING AND ROOT PRUNING

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ABSTRACT

Commercial apple orchards have recently been adopting hedging as an alternative, or supplement, to hand pruning. With rising labor costs across the United States, alternatives to hand pruning and current training systems require consideration. One management strategy is the transition from a tall spindle tree training system to a narrow tree wall, facilitating some worker-related aspects of apple tree production such as pruning, harvesting, and fruit thinning. The narrow tree wall's main objective is the creation of a "fruiting wall", manipulating tree canopies to make fruit more visible and accessible, facilitating harvesting. The purpose of this study was to evaluate the use of hedging and root pruning to convert orchard training systems into a narrow tree wall. Dormant and summer hedging, along with root pruning, were used to convert 12-year-old 'Brak Fuji' apple trees from the tall spindle training system to a narrow tree wall. Photosynthetically active radiation (PAR) and ultraviolet (UV) light levels were low for all treatments. Light was improved most when root pruning was included. Specific leaf weight was not significantly impacted by hedging or root pruning. Spur sampling showed that treatments had no effect on vegetative or reproductive growth on two- to three-year-old wood. While hedging did not affect shoot length, the combination of hedging and root pruning caused a significant reduction in terminal shoot length. Red fruit color was only improved with the addition of root pruning. Root pruning improved fruit set and yield, but reduced fruit size. Without root pruning, hedging had little effect on light, specific leaf weight, flower initiation, fruit set, and fruit quality. Conversion to a narrow tree wall through manual pruning resulted in more poorly colored fruit and less highly colored fruit compared to maintaining the trees as a tall spindle with manual pruning.

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INTRODUCTION

The effect of light on leaves of an apple tree and fruit quality characteristics are well documented and serve as a guideline for the management of modern apple orchards. It is imperative to allow adequate sunlight penetration in a tree canopy if fruit quality is to be optimized, especially red color development. This can be a crucial factor in the quality characteristics for certain cultivars, where red color development requires high light levels. Most modern apple orchards consist of high-density plantings and orchards must be managed to maximize light interception and distribution throughout the canopy. With renewed interest in hedging and summer pruning, the influence of these practices needs to be evaluated for intensive orchard systems. Although root pruning can suppress tree vigor, growers have been slow to adopt the practice. Root pruning also needs to be considered as an alternative management practice in intensive apple orchards.

Previous studies in Virginia and New York with vigorous central leader trees on semi-dwarfing rootstocks showed little-to-no impact of summer pruning on tree vigor when compared with only dormant pruning. New dwarfing rootstocks are resistant to some pests, control tree size, enhance yield efficiency, and may be used to develop tree architectures well-suited to mechanization to reduce labor. Trees on these new rootstocks may grow less vigorously after summer hedging than trees on more vigorous rootstocks and light levels may be increased throughout the canopy. Root pruning also controls tree size and should help reduce tree vigor and enhance fruit color development in a canopy with sufficient light penetration. Labor costs, especially for pruning, have been increasing, but with efficient mechanization, pruning costs may be greatly reduced.

The objectives of this study were to evaluate the influence of hedging, with and without root pruning, on light distribution in the canopy, vegetative growth, yield, fruit quality and flowering when transitioning to a narrow tree wall in an intensive orchard system.

LITERATURE REVIEW

History of Apple Training Systems in the Mid-Atlantic Region. Before the 1960s, most apple trees were grown on seedling rootstocks, planted up to 12.2 x 12.2 m (67 trees/ha) and trained to a modified central leader with about five scaffold branches arising from the central trunk and the leader was cut to a side limb at about 3 m above ground (Childers, 1969). In the 1960s most orchards were on semi-vigorous clonal rootstocks planted 4.9 x 6.7 m (304 trees/ha) and trained to the central leader system. During the past 20 years, most orchards are planted on dwarfing rootstocks, at densities of 2000 to 3458 trees/ha and trained to some version of the vertical axis with tree support. Multiple leader trees had umbrella-shaped canopies (10m tall) that were inefficient in many ways, prompting the research and development of size-controlling rootstocks (Robinson et al., 1991). Low-density orchards were slow to fill their space and land-use efficiency suffered. In modern high-density orchards, the initial establishment costs are higher than for low-density orchards, but since the trees are kept small and at a greater density, there is greater land-use efficiency and a shorter break-even time for the grower. Low-density apple orchards were less efficient than high-density orchards for a variety of reasons. Fruit color was often lacking due to the tree size and lack of sunlight penetration into the canopy, leading to a decrease in soluble solids concentration (Robinson et al., 1991). With lower light levels within the canopy, much of the crop was more suited for juice and processing, with fruit from the outer canopy being used for fresh market. The use of small apple trees is a means of reducing the unproductive shaded centers of trees (Heinicke, 1975) because yield was related to total light interception (Jackson, 1980). Pest control was more difficult due to the lack of air movement within the trees and poor spray penetration into the canopy (Robinson et al., 1991). The introduction of high-density apple orchards may be “one of the most important changes in apple production practices” (Heinicke, 1975).

Orchard intensification to high-density minimizes some problems faced by growers and offers some significant economic incentives. Suitable orchard land is limited and becoming more expensive, putting more pressure on growers to produce more efficiently on less land to meet their costs and hopefully turn a profit. With this comes the concept of land-use efficiency, where growers are planting more trees per hectare. High-density orchards necessitated size-controlling rootstocks that could make the system feasible (Rom and Carlson, 1987). Without the proper rootstocks, closely spaced trees would quickly crowd one another and without tree removal the whole system would become non-profitable due to severe shading. Adoption of dwarfing apple rootstocks made high-density systems possible and was instrumental in modifying production systems (Tukey, 1964; Rom and Carlson, 1987). Higher demand of better-quality apples required adoption of smaller trees with better light distribution throughout the canopy. In the US, adoption of high-density plantings with dwarfing rootstocks primarily occurred in the latter half of the 20th century and became widely popular. Barritt et al. (1997) published the results from the NC-140 apple orchard system trial which was significant in convincing Washington state growers to implement high-density orchards. Barritt et al. (1997) showed that after five years, the vertical axe training system was the most productive tree training system with the highest yield efficiency when compared to other popular training systems. Barden and Marini (2001) performed a partial economic analysis with 10 years of data from the same NC-140 systems trial and showed that the vertical axis was the most profitable system in the trial. The tall spindle training system is a combination of the slender spindle, vertical axe, and super spindle systems (Robinson et al., 2006) and became popular as a system that could quickly come into production with continued high yield efficiency of high-quality fruit. Current orchard cultivation with tall spindle training systems varies from higher densities of 3,586 trees/ha (1m x 3m) to lower densities of 2,070 trees/ha (1.3m x 4m) (Robinson et al., 2006).

Light Interception and Distribution in Fruit Tree Canopies. Leaves collect solar radiation. In an apple orchard, sunlight has many fates. Some wavelengths of light that are intercepted by leaves are absorbed by leaves and provide energy for photosynthesis. Other wavelengths are transmitted through the leaves. Light that is not intercepted by trees can be absorbed by weeds on the orchard floor. While the plants in the row middles are not detrimental, weeds growing within rows can be a nuisance for growers. Therefore, modern orchards are designed to capture a high proportion of available light for fruit production and minimize the light available for competing plants. With large canopies, fruit developing within the canopy are exposed to less sunlight than those on the outer canopy and have less red color, starch, and sugar (Robinson et al., 1991). Jackson (1980) and Barritt et al. (1991) found that yield was positively correlated with leaf area/ha and with the percentage of light interception.

Adequate sunlight has long been recognized as being critical to produce quality apples. Shade causes “reduced fruit size, through reductions of cell size and number of cells per fruit” (Jackson et al., 1976). The light environment in tree canopies is crucial to the production of apples that are commercially valuable. Campbell and Marini (1992) found a positive linear relationship between the percent of red surface on an apple and cumulative hours of photosynthetic photon flux (PPF) above 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (HR_{250}) of photosynthetically active radiation (PAR). Intensity of red pigmentation and soluble solids concentration also increased linearly with HR_{250}. Light penetration into the canopy is essential for red color development in apples and a synergistic effect of red and UV-B light (280-315 nm) was found to be important in developing the desired red skin color under field light conditions (Arakawa et al., 1985). Cultivar selection is based on meeting buyer demand. Since cultivars require varying amounts of light to develop red color, research is being conducted on some newer cultivars to improve red color, fruit size, etc. For red cultivars like ‘Honeycrisp’ and ‘Fuji’, the amount of sunlight hitting the fruit can determine whether the fruit will be accepted by buyers based on color and size. The starch content and sugar concentration of the fruit is also impacted by shade. Jackson (1976) found that ‘Cox’s Orange Pippin’ fruit grown in shade had less dry matter and starch per unit fresh weight, a relationship found across all cultivars studied.

Marini & Barden (1981) measured specific leaf weight (SLW) and net photosynthesis for apple leaves throughout the season and reported a linear relationship between the two until the end of the growing season, when the relationship became quadratic. Specific leaf weight could be used to describe the light environment in regions of a canopy. “Specific leaf weight appears to be a reliable index of the previous light environment of a leaf, but use to estimate photosynthesis is probably limited to the first half of the season” (Marini & Barden, 1981).

Heinicke (1963) showed that light levels rapidly declined from the tree periphery toward the trunk, and that fruit quality was related to light level (Heinicke, 1966). These two papers contributed to the adoption of the central leader system, where trees had a conical shape that allowed better light distribution throughout the tree. The head and spread system persisted until the early 1990's, when Marini et al. (1993) and others showed that annual branch heading reduced yield. Heinicke (1966) suggested limiting the lower whirl of branches to five branches, but Marini et al. (1993) found that retaining wide-crotched branches until they fruited two or three years could improve yields by up to 30% during the first eight years of the orchard.

Tree canopy architecture has changed quite a bit over the past few decades as tree density increased. Maintaining good light distribution throughout the canopy is a major focus in mature orchards (Ferree and Warrington, 2003). Contrary to the large umbrella-shaped trees, central-leader systems have a pyramid-shaped tree with tiers of branches spaced along the trunk. The non-supported central leader is a medium-density system, utilizing semi-dwarfing rootstocks, with tree densities ranging from 300 to 700 trees per hectare (Ferree and Warrington, 2003). The slender spindle described by Wertheim (1968) used dwarfing rootstocks and was designed to improve early yields and management efficiency by planting higher tree densities. These trees were supported by a single stake or single- to three-wire trellis from the year of planting on. Lespinasse (1980) introduced the vertical axe system in southern France and utilized tree densities from 1000 to 2500 trees per hectare, spaced anywhere from 1-2m within the row and 4-5m between the rows (Ferree and Warrington, 2003). Robinson et al. (2006) began using the term tall spindle system to refer to a combination of previous systems. This system became popular in North America and is currently an important system used by many commercial orchards.

Light quality is a promising area of research that could be used as a new technological alternative for sustainable production of horticultural crops (Bastias and Corelli-Grappadelli, 2012). Light quality has a major impact on fruit color development. Red peel color is due to anthocyanin pigments, mainly cyanidin 3-glactoside (Ju et al., 1999; Awad et al., 2001; Layne, 2001; Bastias & Corelli-Grappadelli, 2012). Red light has a lower effectiveness on fruit color development than UV-B light, but the synergistic effect of red light plus UV-B results in even greater fruit color development (Arakawa et al., 1985). Removal of branches through pruning cuts improves PAR distribution within tree canopies, allowing for greater light interception throughout the tree. UV light penetration into the canopy of commercial apple orchards has not been adequately studied.

The Role of Pruning in Apple Orchards. Trees respond differently to various types of pruning cuts. There are three types of pruning cuts commonly used in apples. The first type is heading (or heading-back) cuts. Heading involves removing the terminal portion of a shoot (Childers, 1969; Marini, 2020) along with terminal buds that would normally inhibit development of axillary buds below the terminal. These cuts result in a thicker and denser canopy on the periphery of the tree that limits light penetration into the tree canopy. Heading into older wood can convert potentially fruitful spurs to non-fruitful vegetative shoots (Marini, 2020). The second type of cut is a thinning cut, which removes an entire shoot or branch at its point of origin. Unlike heading cuts, these cuts do not induce vigorous growth in the vicinity of the cut and are used to open the tree’s canopy to allow more sunlight to penetrate the interior of the tree canopy. In general, thinning cuts are associated with increased apple flower bud production and heading-back cuts encourage branching. The third pruning cut is a bench cut, which is an adaptation of a heading cut where the cut is made at a point just above a side branch (Marini, 2020). Bench cuts are used to remove the upright portion of a branch while promoting the outward growth of the branch. When possible, limb spreading is preferable to bench cuts.

Tree pruning is an integral part of any commercial fruit tree orchard to improve light penetration into the canopy and to balance reproductive and vegetative growth. Fruit growers may underestimate the importance of this balance, which can cause detrimental downstream effects from an imbalance between these two factors, such as the greater prevalence of biennial bearing. Sagong et al. (2015) showed high density ‘Fuji’/M.9 orchards were prone to biennial bearing at higher crop loads. Trees that are over-cropped also produce small fruit with low soluble solids and poor red color (Ferree and Schupp, 2003). In high-density orchards trees sometimes lack adequate vigor due to dwarfing rootstocks, along with tree-to-tree competition, resulting in low yields, and small, poorly colored fruit (Marini et al., 2006). With judicious dormant branch removal, crop load is partially managed by removing flower buds. Fresh market apples are graded based on size and color. Inadequate crop load management may lead to poor quality fruit and impact potential profits (Harper et al., 2013). It is also important to note that some cultivars are more prone to biennial bearing than others. ‘Fuji’ and ‘Honeycrisp’ are sensitive to biennial bearing and crop load needs to be managed carefully (Fioravanço and Czermainski, 2018), whereas cultivars like ‘Rome Beauty’ and ‘Gala’ can carry heavy crops every year (Howlett, 1970).

Heading cuts have been used to induce branching and stiffen branches. In the 1970s, the head-and-spread central leader system was common, where leaders and scaffold branches of young trees were headed by ~25% to promote lateral branching and stiffen the branches, allowing young trees to be established with little or no support (Lord and Costante, 1977). Over the years, heading of the leader was replaced by bud notching (Greene and Autio, 1994) and application of hormones to promote the distribution of scaffold limbs evenly along the central leader (Forshey and Elfving, 1976). Marini et al. (1993) found the removal of scaffold limbs and annually heading 1-year-old wood, as recommended by Heinicke (1974) for spread and head central leader training, can have a long-term negative effect on productivity and orchard profitability. This supported the findings of other researchers (Elfving, 1990; Gardner, 1917) that young trees on dwarfing rootstocks should be supported, and pruning should be minimized. Therefore, nonselective pruning cuts made by hedging may have negative effects. These hedging cuts could potentially result in a proliferation of branches below the cut resulting in a shell of dense canopy that interferes with harvest operations and increases shade.

Supporting young trees on dwarfing rootstocks, combined with minimal heading and scaffold limb removal was more profitable than heading non-supported trees (Barden and Marini, 1998). Supported young trees with stakes or trellises promote vertical leader growth to encourage early fruiting and a quicker return on investment. The “fruiting wall”, one of the systems studied in this project, is a modification of the tall spindle, where the trees are encouraged to fill their space horizontally within the row and vertically, forming a narrow wall of vegetation that facilitates tree management and fruit harvest. Some growers would like to convert tall spindle plantings to fruiting walls and this might be achieved with hedging. One of the purported benefits of hedging is the creation of a fruiting wall (Lewis, 2018; Robinson, 2013; Robinson, 2013a). The formation of a fruiting wall could assist in harvesting and facilitate mechanical/robotic harvesting with the appropriate technology.

Proper pruning controls tree size and shape through wood removal to improve light distribution throughout the canopy. The tree fruit industry is interested in mechanization of orchard practices to reduce labor costs, but orchards with varying tree size/shape within and between rows creates challenges. Trees can be pruned to produce trees with the sizes and shapes that are conducive to mechanization. Schupp et al. (2017) showed that although fruit set increased with increasing pruning severity, fruit number per tree, yield efficiency, and yield decreased with increasing number of limbs removed. Research on manual detailed pruning resulted in a wide variety of tree training systems that are used today. While these systems may vary in overall shape and structure, the general trend over the last 20 years has been toward high-density, intensive systems with closely spaced trees with a pyramid shape for greater light interception.

Differentiating Pruning and Hedging. The terms “pruning”, “hedging” and “mechanical pruning” are often used interchangeably which leads to confusion in the literature. For this paper the terms are defined as follows. “Pruning” is the selective removal of limbs, shoots, and spurs to balance vegetative and reproductive growth and maintain tree size and shape. Proper pruning enhances air movement and light penetration throughout the canopy for production of high-quality fruit. Pruning while leaves are on the tree is termed “summer pruning” and can be done to remove large branches and upright water sprouts that would be removed during dormant pruning to reduce shade. Historically, summer pruning involved heading of one-year-old shoots one to three times during the summer (Marini and Barden, 1982; Tukey, 1964; Utermark, 1977), although some experiments involved thinning cuts during the summer (Autio and Greene, 1990).

Pruning is essential to any orchard production system. With the domestication of tree fruit into man-made systems, pruning was used to force trees to adapt and fit our needs. In high-density apple orchards, pruning is crucial to maintain the desired tree size/shape and adequate light levels throughout the canopy. While low-density systems were also pruned, high-density systems sometimes require more severe and detailed pruning to prevent overcrowding and excessively large trees. Pruning is the second largest labor expense for apple production and can account for “20% or more of total production cost in the full production years” (He and Schupp, 2018). Apple growers are interested in cost-reducing practices and hedging has been proposed as an inexpensive tool to manage vegetative growth and shape the canopy for enhanced light penetration and distribution.

“Hedging” involves nonselective heading of mostly one-year shoots with a cutting bar/mower. Hedging performed while leaves are on the tree is termed “summer hedging”. Considering rows of trees, the goal of hedging is often to develop a canopy with a certain height and shape, usually an angled wall. The terms “hedging” and “mechanical pruning” are often used interchangeably. Since pruning refers to selective removal of shoots and limbs, hedging is the term that will be used in this paper when referring to nonselective pruning of trees with a cutter bar.

Hedging as a Management Technique. Tall spindle training systems make pruning easier and remove some of the “art” that is often associated with pruning. Interest in mechanized pruning has increased greatly with the implementation of high-density orchards. Hedging makes non-selective heading cuts as the blades run alongside the tree row, forming what is commonly called a “narrow tree wall”. Hansen et al. (1968) implemented dormant hedging with little experimental evaluation and developed a dense shell of shoot growth on the canopy periphery that shaded the interior canopy and reduced fruit quality. Ferree (1976) emphasized the need for supplemental manual pruning following dormant slotting-saw hedging of trees to reduce shading in the interior fruiting areas. According to Ferree (1976), pruning was responsible for more than 30% of production costs with large central leader trees and Marini & Barden (2004) reported similar results for trees trained to the vertical axe system. Shading and tree crowding are major concerns that could negatively impact the marketability of fruit, forcing the implementation of more severe pruning. Orchardists have been shifting focus to these hedging tools as a pruning alternative and are looking to develop narrow tree walls. A transition from tall spindle to narrow tree wall through hedging during the summer would potentially increase light penetration into the canopy and facilitate mechanical harvesting. Even without mechanical harvesting, the resulting “fruiting wall” is easier to harvest by hand. Previous research determined “orchard intensification is accomplished best by choosing appropriate planting distances and not by attempting to control growth mechanically on trees planted too close for optimum performance” (Ferree & Rhodus, 1993). Ferree & Rhodus (1993) used trees at 370 or 1429 trees per hectare. Over time, tree spacing recommendations have evolved to higher tree densities. Current recommendations by Robinson et al. (2013a) state the optimum planting density is approximately 2,700 trees/ha, although super spindle orchards can be around 5,450 trees/ha or even more.

Although results from hedging experiments with central leader trees on semi-vigorous rootstocks were disappointing, some growers and researchers have been re-evaluating hedging as an alternative to manual pruning in high-density orchards on dwarfing rootstocks to control tree vigor and enhance yield and fruit quality (Milkovich, 2020). Hedging is performed with a large blade or cutting bar that non-selectively removes the ends of branches at a certain distance from the trunk, which can potentially lead to a dense canopy shell preventing light penetration that may negatively affect fruit quality (Mika et al., 2016). After three years, trees hedged at pink or about three weeks after bloom had higher yields than manually pruned trees, but fruit size and red color were reduced due to lower light levels. To alleviate shading and the subsequent negative effects induced by hedging, Mika et al. (2016) suggested that hedging must be supplemented with hand pruning and additional attention must be given to fruit thinning.

Since manual pruning is expensive and requires skilled labor, and hedging often has negative consequences, it may be feasible to combine hedging with new cultural practices. Prohexadione calcium, (PCa) is a naturally occurring gibberellin inhibitor that was registered in 1997. When applied to apple trees it reduced terminal shoot growth an average of 59% compared to controls (Glenn and Miller, 2005; Uselis et al., 2020). PCa also reduced the weight of prunings removed annually from the tree (Uselis et al., 2020). Three to five applications of PCa are commonly used in commercial orchards to suppress June drop, suppress shoot growth, and suppress fire blight infection (Crassweller et al., 2020). Early-season PCa applications may reduce the negative effects of hedging by suppressing shoot growth induced by heading cuts.

Summer hedging is currently recommended when terminal shoots have 12-14 expanded leaves (Lewis, 2018). The goal of these recommendations is to push buds on blank wood on older branch sections, but supporting data are lacking. Detailed evaluation of branch sections is necessary to evaluate the influence of summer hedging on vegetative and reproductive characteristics of branches and to determine if flower bud formation and fruit set can be improved. The quantity and quality of light within the canopy should also be considered when trying to increase fruit production in the interior canopy where red fruit color for some cultivars is difficult to obtain.

Summer Pruning for Growth Control. In the late 1970s summer pruning was suggested to enhance fruit color and quality, suppress tree vigor, and increase light penetration, resulting in improved flower bud initiation, and fruit set (Utermark, 1977). Unlike dormant pruning, summer pruning is practiced when leaves are on the tree and often before terminal bud set. The method of summer pruning suggested by Utermark (1974) involved heading current season shoots to three or four leaves about four weeks before harvest. Preston and Perrin (1974) showed that summer pruning often improved fruit storage quality by reducing bitter pit, internal breakdown, and water-core. This reduction can primarily be attributed to the increase in fruit calcium following summer pruning. Hayden and Emerson (1976) suggested hedging high density peach plantings twice (July and August) as a method of tree containment, while stressing that dormant hedging resulted in “excessive shoot proliferation in the outer canopy and required considerable detailed corrective pruning, while trees summer hedged twice each year did not have this problem” (Ferree 1984; Hayden and Emerson 1976). Ferree (1979) found dormant hedging apples reduced canopy spread but was an acceptable practice when combined with biennial hand pruning.

Summer pruning theoretically suppresses vegetative growth by reducing whole-tree photosynthesis and carbohydrate reserves used for growth the following year. Marini & Barden (1982) measured shoot growth on summer- and dormant-headed vigorous mature trees and one-year-old container-grown trees. When all one-year-old shoots were headed to three leaves in the summer or three buds in the winter, the shoot growth response was similar. Heading cuts induced the same shoot growth whether the heading cuts were made in the summer or dormant season, but the response was delayed until the following year for summer-pruned trees. Compared to dormant pruning, the season following summer pruning light levels were not increased in summer pruned trees until they were again summer pruned the second year. Following summer pruning, light distribution was enhanced throughout the canopy and leaves from the tree interior had higher specific leaf weight and higher photosynthetic rates, but fruit red color, flower bud formation and fruit set were not consistently affected by time of heading. Saure (1987) cited delayed apple fruit development and later induction of dormancy as some of the main drawbacks associated with summer pruning in apples. Marini (1986) also found that summer hedging delayed leaf abscission and cold acclimation in peach. In areas with a short season, summer pruning could delay or prevent the onset of dormancy, which has adverse effects on winter hardiness. The positive influence of summer pruning was an improvement of fruit color through better light penetration into the canopy (Saure 1987).

Cultivars such as ‘McIntosh’ that are considered difficult to color had a dramatic improvement in red fruit color when trees were summer pruned with thinning cuts to remove limbs that caused shading rather than by heading shoots (Autio and Greene, 1990). Summer pruning with thinning cuts is an effective method of reducing leaf/stem area without risking current-season regrowth. Regrowth from heading cuts in the current season is reduced or eliminated if summer pruning is performed 1-2 months before harvest but after terminal buds have formed (Ferree and Warrington 2003).

In the past decade, summer hedging has been proposed to control vegetative growth, improve light penetration within the canopy, and improve red fruit color in intensive orchards (Gandev & Dzhuvinov, 2014; Lewis, 2018; Robinson, 2013a; Rosecrance et al., 2021). Although several articles appearing in trade journals mention summer hedging is essential for commercial operations, there are few data or evidence to support these claims. The claim is that summer hedging after terminal bud set will not stimulate proleptic shoots because the trees have already stopped producing new shoots for the year. In intensive orchards regrowth is often short and terminal buds are often flower buds (T. Robinson, personal communication). Additional work is needed to determine if summer hedging increases flower bud formation and fruit set and suppresses shoot growth the following season in intensive orchards.

An Overview of Root Pruning. Root pruning is another vegetative growth control method. Root pruning is not a novel concept and has been previously studied, although adoption is limited. Schumacher (1975) found root pruning to be effective only when the correct number of roots were cut; cutting too few roots led to excessive root development and shoot growth, while excessive root cutting could lead to tree death, especially in dry years. The correct amount of root pruning terminated shoot growth early and encouraged flower bud initiation.

Established bearing fruit trees growing in northern regions have a single shoot growth flush (Head, 1967) of much shorter duration than newly transplanted trees, where root and shoot growth occur concurrently (Atkinson, 1980), explaining the stronger response to root pruning for established trees. Results from root pruning vary based on the severity of pruning treatment. Schupp & Ferree (1990) suppressed shoot diameter with all root pruning treatments, but Rom (1982) reported no effect on shoot diameter. Root pruning 3-year-old container-grown ‘Fuji’ apple trees suppressed coarse root length while simultaneously increasing leaf chlorophyll content and transpiration rate (Fang et al., 2017), indicating that roots are often produced in excess, and apple trees can compensate for localized disruption to the root system.

McArtney & Belton (1992) found root pruning apples during the dormant season and at petal fall “resulted in a significant reduction in mean leaf area of shoot leaves”. Root regeneration after pruning is more prone to branching, increasing absorbing surface, suggesting that nutrient uptake will be similar to non-root pruned trees (Geisler and Ferree, 1984). Water absorption will obviously be reduced with root pruning and could potentially cause water stress in the plant, as reported for holly (Randolph and Wiest, 1981) and maize (Brevedan and Hodges, 1978). Andrews and Newman (1968) compared the growth of root pruned vs. non-root pruned wheat plants with and without drought stress. Root pruning reduced growth of watered plants, but there was some indication that root pruning increased growth in the dry treatment. Root pruning could help acclimate an orchard for future drought events by simulating drought stress and promoting acclimation, although this should not be the sole reason for root pruning.

Schupp and Ferree (1988) found no reduction in yield following root pruning, and the positive impacts included controlling tree size, and increased yield efficiency and fruit quality in vigorous cultivars. However, in drier years, fruit size was reduced following root pruning (Schupp and Ferree, 1988). Root pruning at full bloom increased fruit total soluble solids (TSS) concentration and slightly increased fruit firmness, although starch hydrolysis was decreased at harvest (Schupp et al., 1992). Schupp et al. (1992) also found no impact of root pruning on return bloom, fruit set, or yield.

Root pruning has also been studied on other fruit trees. Yang et al. (2009) found that root pruning decreased branch length in Zhanhuadongzao trees (*Ziziphus jujube* Mill.). Root pruning on sweet cherry trees did not consistently affect floral bud production, fruit set, or fruit size (Webster et al., 1997). Results were variable based on fruit crop and climate. At higher crop densities, mean fruit weight was lower on root pruned apple trees (McArtney & Belton, 1992). As crop density decreased, the mean fruit weight of root pruned treatments approached those of controls. Root pruning can reduce mean fruit weight and affect the marketability of these fruit. Some trees can have suppressed vegetative growth when root pruned due to proportion of root system removed. Uselis et al. (2020) reported that root pruning on one or two sides of the tree resulted in reduced trunk cross-sectional area and shorter average shoot length. Root pruning also increased the number of shoots per tree, yield, yield efficiency and fruit red color, but reduced fruit weight, and the response was slightly greater when two sides of the tree were root pruned. In high-density orchards (slender spindle trees, 3170 trees/ha), root pruning decreased the average length of annual growth and increased tree productivity (Mitre et al., 2012).

Previous Findings with the Future in Mind. With the modernization of the world and the increased interest in automation, there is a need for scientific investigation into hedging and root pruning to lower the expenses of hand pruning and help shape an orchard that is adapted quickly to new technologies. Research results with mechanical harvesting are promising (He and Schupp, 2018) and the harvesting technology may soon be commercially available. However, closely spaced trees on dwarfing rootstocks that are hedged to transition trees to "fruiting walls" may respond differently. Hedging combined with PCa and/or root pruning may suppress tree vigor, increase light penetration, and improve flower bud formation and fruit set more than hedging alone. Therefore, it is important to study the effectiveness of hedging and root pruning on converting apple trees from a tall spindle to narrow tree wall training system.

Project Objectives. The objectives of this research were to evaluate summer plus dormant hedging, with and without root pruning to transition tall spindle trees to a narrow tree wall (NTW) system. We particularly wanted to determine if summer hedging with or without root pruning will suppress tree vigor and improve fruit quality and yield in NTW trees. Three hypotheses are being tested in this experiment: tall spindle training systems compared to narrow tree wall training systems using manual pruning; narrow tree wall training systems using manual pruning compared to dormant and summer hedging; and narrow tree wall training systems using dormant and summer hedging compared to dormant and summer hedging plus root pruning.

MATERIALS & METHODS

Plant Material and Experimental Setup. Twelve-year-old ‘Brak Fuji’/M.9 T337 apple trees growing at the Pennsylvania State University Fruit Research & Extension Center in Biglerville, Pennsylvania (39.93483219156932, -77.25520773107269) were used for the study. The trees were trained to a tall spindle trellis with 3 wires at 1.25, 1.88, and 2.5m above ground. Tree spacing was 0.9m x 3.74m. Tree rows were approximately 100 m long and oriented north south. Summer hedging was done in early summer when trees had 15-17 fully expanded shoot leaves with a tractor mounted FAMA hedger (Provide Agro, Beamsville, Ontario, Canada). The hedger bar was set at 45.7 to 50.8cm from the trunk during dormancy and 55.9 to 66 centimeters from the trunk during the growing season per current recommendations (Courtney and Mullinax, 2016). All trees received four applications of prohexadione calcium (Kudos, Fine Americas, Walnut Creek, California) at 841 grams per hectare, starting at petal fall and at 21-day intervals thereafter. Fertilization, irrigation, and pest management followed local guidelines (Crassweller et al., 2020).

The experimental design was a randomized complete block design with 5 blocks. Each experimental unit was a plot of 10-15 consecutive trees. In Feb. 2020, the following 4 treatments were established on each set of trees: 1) standard manual dormant renewal pruning to maintain tall spindle form; 2) manual dormant pruning with the intent of transitioning the training system to a narrow tree wall with 5-6 renewal cuts; 3) dormant mechanical hedging with the intent of transitioning the training system to a narrow tree wall with 5-6 manual renewal cuts, followed by hedging in June (summer hedging) when shoots had 12-14 leaves; 4) dormant hedging with the intent of transitioning the training system to a narrow tree wall with 5-6 manual renewal cuts and hedging in June (summer hedging) when shoots had 12-14 leaves, coupled with root pruning. Root pruning was done at pink bud stage using a tractor-mounted root pruner (Phil Brown Welding Corp., Conklin, Michigan) with cuts made on both sides of the row at 50 cm from the trunk to a depth of 25 cm. Root pruning was done at 1.0-1.1 mph.

Light & UV Measurements. Photosynthetic photon flux of photosynthetically active radiation (PAR) was reported instead of full sun because Rom (1991) referenced the importance of "documenting and reporting appropriate units of light flux and total light absorbance or interception" because percent full sun does not provide a description of irradiance flux at a point in time or total irradiation over time. PAR was measured with a LI-COR LI-250A light sensor equipped with a LI-COR LI-191R line quantum sensor (LI-COR BioSciences, Lincoln, Nebraska). PAR was measured at three canopy heights on each of five trees per experimental unit (N=300). PAR was measured at 1, 2, and 3 m above the ground corresponding to the lower, middle, and upper tree canopy. Middle and upper canopy measurements were taken using the NBLOSI (self-propelled labor platform). The light sensor was placed halfway through the canopy on the south side of the tree approximately 15cm from the trunk with the operator standing to the north of the sensor. References were taken before and after each measurement if light conditions were not stable. When there were scattered clouds, references were taken before and after each tree. Light was measured 3 different times during the growing season. PAR was measured before summer hedging (14 June 2021), after summer hedging (23 June 2021), and after shoot growth had ceased (24 August 2021).

UV light was measured at eight canopy locations on five trees per experimental unit with a LightScout UV meter (Spectrum Technology, www.specmeters.com) on 19 and 20 July 2021 (N=800). UV light was measured approximately 15cm from the trunk on the north, east, south, and west side of each tree at about 1.0m and 3.0m above ground.

Specific Leaf Weight. Specific leaf weight was used to evaluate treatment effects on the previous light environment of leaves. On 17 June 2021 eight shoot leaves were sampled from each of six trees per experimental unit. The leaves were the newest fully expanded leaves on a current season shoot that were expected to be approximately mid-shoot by the end of the growing season. Four leaves were sampled at approximately 152cm from the ground on the west and east sides of each tree (N=48).

On 17 June 2021, spurs with leaves were sampled at approximately 152cm from the ground on two- to three-year-old wood at approximately 30cm from the trunk. One non-fruiting spur from the west and east side was sampled from each of the five middle trees per experimental unit (N=10). All leaves were removed from spurs and counted. Total leaf area per spur was recorded with a Li-Cor Model LI-3000 portable leaf area meter (LI-COR Biosciences, Lincoln, NE) and leaf dry weight was recorded to calculate the specific leaf weight. Specific leaf weight was used to evaluate treatment effects on the previous light environment of leaves.

Shoot measurements. One terminal shoot on the east and west side of two trees per experimental unit at five canopy positions was tagged and measured at 110, 180, 250, 320 and 390cm above ground. Shoots were measured on 14 and 15 June 2021 and again on 24 September 2021. While measuring shoots in September, each tagged shoot was designated as 1 if it was headed and 0 if it was not headed. For the headed shoots the number of proleptic shoots arising below the heading cut was recorded as well as the length of the most terminal proleptic shoot arising below the cut.

Dormant Branch Analysis. In February 2021, two limbs were removed from their points of origin from the main trunks of two trees per experimental unit. One limb was sampled from the upper third of the canopy (~3 m) and one from the lower third (~1 m). The limbs were renewal limbs, about four years old, were characteristic of most limbs on the tree, oriented slightly above horizontal, and expected to be the "workhorse" limbs in 2021 that would carry a crop of fruit on spurs and terminal buds.

The length of every shoot arising along the limb was measured starting at the base of the limb, usually four-year-old wood that originated in 2017. For a four-year-old limb, growth arising from the 2017-, 2018-, 2019-, and 2020- wood was measured. The presence and absence of dormant- and summer-hedging cuts was recorded for each shoot developing in 2020. The average length of a shoot that grew in 2020 was calculated and used for analysis. All proleptic shoots developing behind summer hedging cuts in 2020 were also measured.

Blossom Counts/Final Fruit Set. Blossom clusters on four uniform branches per experimental unit were recorded 15 and 16 April 2020 (N=80). One branch was selected from the upper canopy, approximately 3.0 to 3.5m above ground and two branches were from the lower canopy about 1 to 1.3m above ground on the north and south sides of the row.

Branch circumference at the point of origin on the trunk was recorded. Starting with 2017 wood and moving along the limb to more recent growth, each short shoot (<4 cm) was measured and marked as flowering or non-flowering (1 or 0). Longer shoots with flowers were also counted. On 2020 growth, the type of flower cluster was recorded as spur flowers (flower clusters on lateral shoots <4cm long) or terminal flowers (flower clusters arising from the terminal buds of shoots > 4cm). On 20 July 2021, final fruit set was recorded on the same branches used for blossom counts. Fruit set was expressed as fruit/100 flower clusters.

Fruit Quality. Two trees per experimental unit were harvested in late October both years. In 2020 and 2021 all fruits were weighed on an electronic single-lane fruit sizer equipped with a digital load-cell (Durand-Wayland, Inc., LaGrange, GA). In 2020 and 2021, 20 fruits per tree (N=800) were used to evaluate fruit quality. The percentage of the fruit surface colored red was recorded. Flesh firmness was measure on two sides of each fruit with a Guss Fruit Texture Analyzer (QA Supplies, Norfolk, VA) and juice collected to measure soluble solids concentration with an Atago PR-32 refractometer (Atago, USA, Inc., Bellview, WA). Each fruit was cut horizontally, and the cut surface was dipped in iodine solution to evaluate starch hydrolysis on a scale of 1 to 8 (Blanpied & Silsby, 1992). Crop density was calculated from trunk cross-sectional area (TCSA) measurements recorded after harvest in 2020 and 2021.

Data analysis. Data for PAR, UV measurements, dormant branch analysis, blossom counts, and fruit set on each date were analyzed with analysis of covariance with SAS's Proc Mixed, where treatment was a fixed effect, block was a random effect, and canopy height was a regressor variable. The approach by Milliken and Johnson (2002) was followed. Each response variable was analyzed by fitting the full model with treatment, position, and tree height, plus the four interactions. When the interaction was not significant, treatment LSmeans were compared with single degree-of -freedom contrasts.

Specific Leaf Weight. Data were analyzed with analysis of variance with SAS's Proc Mixed, where treatment and tree side were fixed effects and block was a random effect. Treatment LSmeans were compared with single degree of freedom contrasts.

Shoot Measurements. Data were analyzed with analysis of covariance, where treatment and tree side were fixed effects, block was a random effect, and canopy height was a regressor variable. Plots of shoot length before and after summer hedging vs. canopy height exhibited a curved pattern, suggesting a quadratic response. Each response variable was analyzed by fitting the full model with treatment, tree side and the linear and quadratic terms for canopy height, plus all interactions. The interaction with the highest nonsignificant P-value was deleted and the model was refit. This manual backward elimination was repeated until only significant (P=0.05) factors remained. Treatments were compared with single degree-of-freedom contrasts.

The presence or absence of a cut tagged shoot was recorded as a binary response (yes, no). Binary data are often analyzed with binary logistic regression because residuals are not normally distributed. Logistic regression is an extension of simple linear regression. However logistic models cannot properly account for random effects such as blocks. Therefore, these data were analyzed with Proc Glimmix using individual-event data as described by Kiernan (2018). To avoid biased variance estimates for the variance components, the maximum likelihood method (Method=Quad) was requested. Options in the model statement included the dist=binary and link=logit to request the binomial distribution. The predicted probabilities for each shoot were output to a new data set using the inverse link function in the output statement [predicted(blup ilink)=predprob]. The predicted probabilities were then used in Proc Logistic to generate graphs of the receiver operating characteristic curve (ROC) and the area under the ROC curve (AUC) (Kiernan, 2018). Proc Logistic was also used to compare the ROC curves from competing models (models with different regressor variables).

The ROC curve was developed for operators of military radar receivers, and is commonly used in psychophysics, medicine, and radiology to predict a binary outcome (Park et al., 2004). In the current study there were four potential outcomes when predicting whether or not a shoot would be cut: 1) "true positive" when a model correctly predicts a shoot will be cut; 2) "true negative" when a model correctly predicts a shoot will not be cut; 3) "false negative" when a model incorrectly predicts a shoot will be cut; and 4) "false positive" when a model incorrectly predicts that a shoot will be cut. A ROC curve is a plot of a test's sensitivity (y-axis), which is the true positive rate, against 1-specificity (x-axis) which is the false positive rate (Gönen, 2006). To produce ROC curves, the predicted probability is transformed into a dichotomy using thresholds and reporting results for each threshold, where each point on the curve corresponds to a specific threshold. The points can be connected to produce an empirical ROC curve. ROC curves may be enhanced by including a 45-degree line. This reference line represents the ROC curve for a random guess (50% chance of correctly classifying a shoot as being cut) and is sometimes called the "chance diagonal". A model that accurately predicts a cut shoot will produce a curve that ascends very quickly and vertically from the origin towards the upper left corner of the plotting area, then curves quickly to the right with a long flat line across the top of the chart (Fig. 1). AUC is the most popular method of summarizing the accuracy of a model with a single number (Gönen, 2006). A model with predictions that are 100% wrong has an AUC of 0.0, and a model with predictions that are 100% correct has an AUC of 1.0. A model with an AUC of 0.5 is correct half the time and is no better than flipping a coin. In general, an AUC of 0.5 indicates that the model has little discriminatory ability and cannot accurately classify shoots that will be cut. An AUC of 0.7 to 0.8 is considered acceptable, 0.8 to 0.9 is considered excellent, and >0.9 is considered outstanding (Hosmer and Lemeshow, 2000). AUC curves of a variable are often compared to chance (Shin and Coulter 2009); when the estimated AUC is statistically greater than 0.5, there is evidence that the model is useful for correctly classifying shoots that will or will not be cut.

Comparison of fruit size distributions. The empirical distribution function (EDF) is a nonparametric estimate of the cumulative distribution function and is used to describe a sample of observations of a given variable, in this case FW. The value of the EDF at a given point is equal to the proportion of observations from the sample that are less than or equal to that point. The nonparametric Kolmogorov– Smirnov two-sample test, obtained with SAS's PROC NPAR1WAY, was used to test equality of EDFs for three pairs of treatments.

RESULTS & DISCUSSION

Light & UV Measurements. Pre-hedging PPF levels were not affected by treatment the previous year (Table 1). On 23 June, post-hedging PPF levels were similar for TS and TW, and for TW and TW DH+SH, but PPF was higher for TW DH+SH+RP than TW DH+SH. When measured in Aug., PPF levels were higher for TW DH+SH than TW, and PPF levels were higher for TW DH+SH+RP than TW DH+SH; UV levels were higher for TW than TS and UV levels were higher for TW DH+SH+RP than TW DH+SH.

Both pre- and post-hedging PPF declined from the top of the canopy to the bottom, but the lowest position was not always different than the middle. The treatment by canopy position interaction was not significant for all response variables (Table 1). UV light was significantly greater in the high position in the canopy when compared to the low position.

Table 1. The influence of three pruning treatments to transition trees from tall spindle (TS) to tree wall (TW) on photosynthetic photon fluxes (PPF) and ultraviolet (UV) light in ‘Fuji’ apple trees in 2021.

	Pre-hedging PPF (% ambient PAR)	Post-hedging PPF (% ambient PAR or UV)		
Treatment[z]	14 June	23 June	8 Aug.	UV
1 TS	8.5	7.7	8.8	5.2
2 TW	10.9	9.3	11.0	6.9
3 TW+DH+SH	10.5	11.7	13.7	6.8
4 TW+DH+SH+RP	10.8	14.4	17.1	9.7
Contrast P-Values				
1 vs. 2	0.1061	0.2068	0.1070	0.0437
2 vs. 3	0.7850	0.0721	0.0428	0.9411
3 vs. 4	0.8280	0.0431	0.0121	0.0005
Position				
High	21.2a[y]	20.3a	23.2a	10.25a
Middle	6.6b	9.3b	8.9b	- - -
Low	2.7b	2.7c	6.0b	4.06b
ANOVA P-value				
Treatment (T)	0.3215	<0.0001	<0.0001	<0.0001
Position (P)	<0.0001	<0.0001	<0.0001	<0.0001
T x P	0.0548	0.3115	0.2766	0.2026

[z] Trees were summer hedged on 16 June, PPF was measured on 14 June, 23 June, and 8 Aug., and UV light was measured on 20 July. Treatments were: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

[y] Means within columns followed by common letters do not differ at the 5% level of significance, by Tukey-Kramer test.

TW DH+SH+RP had the highest PPF levels after summer hedging, but the increase was likely inadequate to affect fruit quality (Table 7). Ferree (1984) stated “It is well known that 30% full sun is needed to saturate photosynthesis of apple leaves and to initiate flower buds”. Light levels at all positions for all treatments were well below 30%. The wand was placed at the same distance from the trunk for all treatments. Because the tall spindle trees had greater canopy spread, the wand was placed further into the canopy than for the tree wall treatments and may explain why tall spindle trees had slightly lower light levels. For hedged treatments, the light levels were still lower than desired due to shade caused by the shell of foliage resulting from the previous year’s hedging.

Therefore, summer hedging likely did not improve light penetration enough to influence fruit quality or flower bud initiation.

Specific Leaf Weight.

Table 2. Shoot and spur specific leaf weight (mg·cm^{-2}) on 'Fuji' apple trees in 2021 as influenced by three treatments to transition tall spindle (TS) trees to tree walls (TW).

Treatment[z]	Shoot SLW	Spur SLW
1 TS	7.27	5.83
2 TW	7.30	5.86
3 TW+DH+SH	7.63	5.79
4 TW+DH+SH+RP	7.56	5.99
Contrast P-Values		
1 vs. 2	0.8734	0.9204
2 vs. 3	0.1224	0.8191
3 vs. 4	0.7406	0.5381
ANOVA P-Value		
Treatment	0.2209	0.9281

[z] Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Shoot and spur specific leaf weight (SLW) were not influenced by treatments. Shade leaves typically have lower photosynthetic rates and lower specific leaf weight than sun leaves (Campbell, et al., 1992; Marini and Sowers, 1990), and the characteristics of shade leaves can be modified by subsequent exposure to high light levels (Barden, 1974). Marini and Barden (1981) suggested that SLW might be used as a biological integrator of light because net photosynthesis was correlated with SLW throughout the season, with the poorest relationships early and late in the season. Marini and Barden (1982a) found that heading all current-season shoots on a tree in mid-August slightly increased PPF throughout the canopy and delayed the late-summer decline in net photosynthesis and SLW. The delayed leaf senescence was likely not due to increased light because similar post-summer pruning responses were observed for leaves on container-grown trees that were not shaded (Marini and Barden, 1982b). Summer hedging in the current study may not have been severe enough to increase light levels enough to influence leaf physiology.

Shoot Measurements.

Table 3. Average terminal shoot length recorded at five canopy heights on the east and west sides of 'Fuji' apple trees before and after summer hedging^{z} during the 2021 growing season.

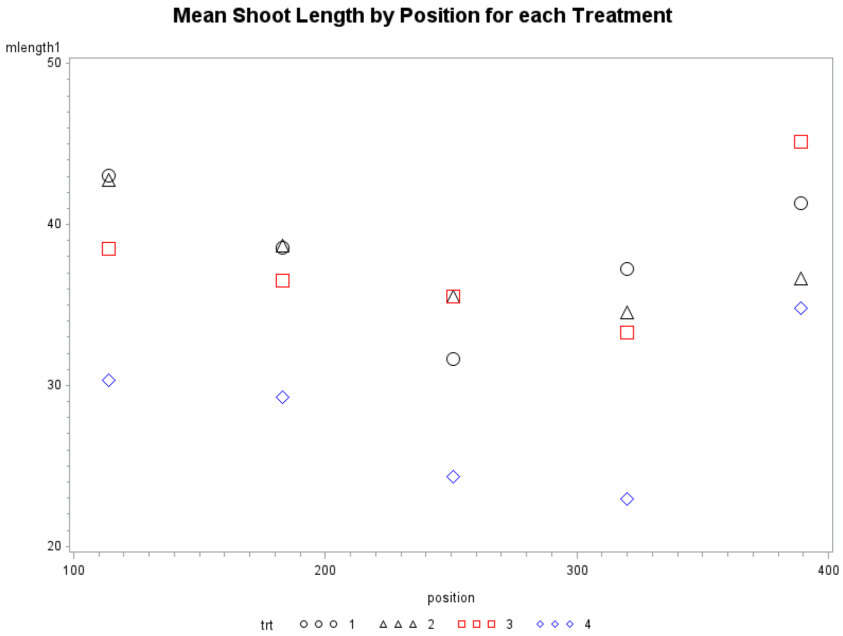
Treatment^{z}	Length (cm) 14 June	Length (cm) 23 June	Regrowth (no. / shoot)
1 TS	38.36	40.15	0
2 TW	37.63	38.93	0
3 TW+DH+SH	37.79	26.08	0.43
4 TW+DH+SH+RP	28.35	18.08	0.50
Contrast P-values to compare treatments			
1 vs. 2	0.7369	0.5189	1.0000
2 vs. 3	0.9431	0.0001	0.4291
3 vs. 4	0.0001	0.0001	0.0650
Height above ground (cm)			
114	38.66	35.37	0.11
183	35.76	29.34	0.18
251	31.74	27.36	0.24
320	32.02	29.94	0.20
389	39.48	32.03	0.44
Side			
East	35.33	30.16	0.24
West	35.73	31.46	0.23
P-values from ANOVA^{y}			
Treatment	0.0001	0.0001	0.3276
Canopy height $_{\text{lin}}$	0.7077	0.1947	- - -
Canopy height $_{\text{quad}}$	0.0001	0.0004	- - -
Tree side	0.7982	0.3551	0.9289

[z] Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

[y] The interactions for trt x side, trt x height, height side x trt, and trt x side x height were not significant at the 5% level.

Terminal shoots were measured before and after summer hedging in 2021 (Table 3). Before summer hedging, treatment TW DH+SH had longer shoots than TW DH+SH+RP. After hedging TW DH+SH had shorter shoots than TW and TW DH+SH+RP had shorter shoots than TW DH+SH. Average number of shoots developing below the heading cut and average length of regrowth shoots were similar for TW DH+SH and TW DH+SH+RP. Average shoot length was related to canopy position in a quadratic manner, where shoot length was greatest at the lower and higher canopy positions (Table 3, Fig. 1). The suppression of shoot growth by root pruning in the current study is consistent with previously reported suppression of apple shoot growth (Schupp & Ferree, 1987).

Figure 1. The influence of canopy position (distance above ground) and treatment^{z} on mean shoot length on ‘Fuji’ apples trees before summer hedging.



^{z} Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Mean shoot length before summer hedging was similar for TS, TW, and TW DH+SH, indicating that hedging did not influence shoot growth the following year and this supports previous reports with apple trees on semi-vigorous rootstocks in the field and grown in containers (Marini & Barden, 1982c). In those experiments, summer heading reduced whole-tree photosynthesis enough to suppress root growth and late-season trunk growth, but trees were able to compensate for this removal of foliage and the following season produced shoots that were comparable in length to trees that were dormant headed. The role of tree carbohydrate reserves is not well understood, along with what triggers the tree to begin using them. Summer hedging is not successful in reducing growth the following year as expected when compared to no summer hedging, indicating a lack of understanding in the role of carbohydrate reserves for early-season tree growth. A better understanding may lead to modification of orchard practices such as pruning, tree training and fruit thinning.

Regrowth of shoots was minimal. Average length of regrowth was < 2 cm (data not shown) and average number of shoots induced by summer heading was < 0.5 per hedging cut (Table 3). Regrowth data were similar for root pruned and non-root pruned trees (Table 3). There are recent reports that there is no regrowth of proleptic shoots after summer hedging (Lewis, 2018), but no data were reported. In the current study, slight regrowth was induced by summer hedging on 43% and 50% of the heading cuts for TW DH+SH and TW DH+SH+RP, respectively, indicating approximately half of the hedged shoots developed regrowth, ranging from short shoots (~ < 3cm) to some surpassing 10cm in length. For ‘Conference’ pear trees 1-sided root pruning twice reduced growth of the tree in times of drought when trees could not be irrigated with no significant effect on fruit quality and flower bud development (Vercammen et al., 2005). Root pruning is known to retard shoot growth (Schupp et al., 1992; Ferree and Rhodus, 1993). Although root pruning affected shoot length before summer hedging, there was no significant impact of root pruning on proleptic shoot development after summer hedging.

Probability of Shoots Being Headed by Hedger.

Since only the hedged trees had shoots that were headed, only the TW DH+SH and TW DH+SH+RP treatments were analyzed with logistic regression. The probability of a shoot being headed was significantly affected by only canopy position (P=0.0104), and treatment, tree side and all interactions were not significant (P<0.60). Although the probability of a shoot being headed was positively related to canopy height, the area under the curve was only 0.6218, indicating that the model with only canopy position had poor ability to classify correctly which shoots will be headed (data not shown).

Dormant Branch Analysis.

Table 4. Total length of all shoots on different age of wood (wood produced in 2017, 2018, 2019 and 2020) from 4-year-old ‘Fuji’ branch sections collected from two canopy positions in March 2020 as influenced by hedging and root pruning in 2019.

	Shoot length (cm)				Shoot number		Regrowth (cm)
Treatment^z	2017	2018	2019	2020	2019	2020	2020
1 TS	.	29.2	40.5	154.4	2.7	9.1	0.6
2 TW	6.8	23.7	33.2	171.0	2.1	7.5	0.1
3 TW+DH+SH	.	28.4	41.7	146.5	3.2	9.2	24.0
4TW+DH+SH+RP	25.9	33.5	38.8	135.0	3.4	9.3	12.9
Canopy position							
Upper	16.5	29.5	36.1	148.53	2.4	8.9	10.9
Lower	16.1	27.9	41.0	154.93	3.4	8.7	7.8
Contrast P-values							
1 vs. 2	.	0.4388	0.4571	0.5759	0.5679	0.8141	0.9455
2 vs. 3	.	0.5018	0.3875	0.4104	0.2981	0.8706	0.0024
3 vs. 4	.	0.4555	0.7561	0.6980	0.8441	0.2302	0.1363
ANOVA P-value							
Treatment (T)	0.1052	0.5288	0.8299	0.6650	0.6073	0.8141	0.0064
Position (P)	0.9058	0.7480	0.4736	0.7600	0.1771	0.8706	0.5504
T x P	0.3495	0.9713	0.3501	0.3570	0.7134	0.2302	0.5299

^{z} Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Mean length and number of shoots on 4-year-old branch sections were similar for all treatments (Table 4). Non-summer hedged treatments had no regrowth, and the combination of summer hedging plus root pruning induced less regrowth than summer hedging alone on 2020 wood. Branch position (upper vs. lower canopy) did not affect any of the response variables measured and the treatment x branch position was not significant.

A previous report with ‘Fuji’ trees indicated that the regrowth induced by summer hedging was always less than 20cm (Lewis, 2018). Marini and Barden (1982c) found total regrowth to increase with summer pruning vs. no summer pruning, and the spring after summer pruning the terminal buds on regrowth did not flower, but usually developed into vigorous vegetative shoots. While recent studies state these regrowth shoots could possess terminal flower buds (Robinson et al., 2013; Lewis, 2018), the terminal ends of the regrowth with flower buds would be removed the following winter with dormant hedging, or the fruit on the terminal ends of regrowth would be removed with summer hedging. Results from our study show a stronger regrowth response to summer hedging (TW DH+SH & TW DH+SH+RP) than reported by Lewis (2018) and closely resembled that found by Robinson (2013). Root pruning coupled with summer hedging (TW DH+SH+RP) suppressed regrowth compared to summer hedging alone, but the difference was not significant at the 5% level. Guidelines set up in experiments performed by Mario Sazo from Cornell University were used for this experiment (Courtney and Mullinax, 2016). Our site was characterized by a silty loam soil with high fertility and good water holding capacity. Crop density may have been a factor affecting the regrowth. There was a light crop 2020 due to frost and there was only a moderate crop in 2021, so trees had adequate reserves for normal growth in 2021. There is no data to support the theory of summer hedging reducing reserve carbohydrates.

Blossom Counts & Final Fruit Set.

Table 5. Mean number of spur and terminal blossom clusters in 2021 on various sections of 'Fuji' limbs following hedging and root pruning treatments in 2020.

	Spur clusters				Terminal clusters	Total clusters
Treatment[z]	2017	2018	2019	2020	2020	
1 TS	0.15	0.35	0.90	0.15	2.25	3.80
2 TW	0.30	0.15	1.30	0.30	2.35	4.40
3 TW+DH+SH	0.15	0.60	0.70	0.35	3.45	5.25
4TW+DH+SH+RP	0.30	1.00	2.60	0.85	2.80	7.55
Contrast P-Values						
1 vs. 2	0.4234	0.5166	0.3803	0.6196	0.8463	0.5279
2 vs. 3	0.4234	0.1473	0.1899	0.8684	0.0363	0.3720
3 vs. 4	0.4234	0.1969	<0.0001	0.1014	0.2105	0.0179
Position						
Upper	0.08b	0.45a	1.98a	0.75a	2.43a	5.68a
Lower	0.38a	0.60a	0.78b	0.08b	3.00a	4.83a
Side						
North	0.15a	0.50a	1.40a	0.40a	2.65a	5.1a
South	0.30a	0.55a	1.35a	0.43a	2.78a	5.4a
ANOVA P-value						
Treatment (T)	0.7300	0.0445	0.0004	0.1174	0.0898	0.0011
Position (P)	0.0262	0.4916	0.0004	0.0024	0.1186	0.2083
Side	0.2588	0.8183	0.8764	0.9068	0.7319	0.6551
T x P	0.8333	0.6739	0.0042	0.1597	0.1110	0.0284

[z] Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Mean number of flowering spurs was not influenced by treatments for 2017- and 2020-branch sections (Table 5). The number of blossom clusters on the 2018 branch section was greatest for TW DH+SH+RP, but contrasts were not significant for the treatment comparisons of interest (TS vs. TW, TW vs. TW DH+SH, and TW DH+SH vs. TW DH+SH+RP). For the 2019 branch section, TW DH+SH+RP had significantly more blossom clusters than TW DH+SH. TW DH+SH+RP had the most total blossom clusters. TW DH+SH had more terminal blossom clusters than TW, indicating that dormant plus summer hedging did induce about 47% more blossom clusters than no hedging.

One of the proposed benefits of heading is its ability to induce flowering on blind wood near the base of the branches (Utermark, 1977). Most of the blind wood referenced in papers supporting hedging is concentrated on the three- and four-year-old portions of branches, correlating to 2018- and 2017-wood in the study. The results of the current study contradict the report by Lewis (2018) because there was no significant increase in flowering on 3- and 4-year-old branch sections, but our results support those of Ferree (1984), Ferree and Rhodus (1993), and Marini and Barden (1982c), where flowering was not enhanced by summer hedging. Results on flowering and fruit set of root-pruned trees was inconsistent across studies and root pruning needs to be reevaluated in modern, commercial intensive apple orchards. Overall flowering was only improved when summer hedging was combined with root pruning. Therefore, it is unlikely that summer hedging will consistently enhance flower bud initiation, except for a slight increase on terminal shoots that will likely be removed by dormant hedging the following winter.

Current hedging recommendations are to set the hedger closer to the trunk during dormancy and farther out from the trunk when summer hedging (Courtney and Mullinax, 2016). One purported benefit of summer hedging is the promotion of flower buds on one-year-old wood, including terminal buds. However, hedging during the following dormant season would remove the potential flower buds that developed. Onset of floral bud differentiation occurs during the summer, mainly beginning in June or July (Kolomiev, 1976; Koutinas et al., 2010). These flower buds would form after summer hedging, only to be cut off by the dormant hedging. If the blade were set closer to the trunk for summer hedging than dormant hedging, the flower buds formed on the wood would not be removed by the dormant hedging, but the resulting fruit might be removed.

Table 6. Final fruit set (fruit/100 clusters) on ‘Fuji’ branches 2021 as affected by three treatments to convert tall spindle trees to a tree wall. Final fruit set for 2018-wood is not reported because there was very little fruit set.

	Fruit set/100 flower clusters on four branch sections				Fruit set
Treatment[z]	2017	2019	2020	Average	Total
1 TS	70	80	325	123.53	480
2 TW	50	155	280	107.29	440
3 TW+DH+SH	55	65	200	57.19	283
4 TW+DH+SH+RP	125	245	260	90.05	660
Contrast P-Values					
1 vs. 2	0.1694	0.1713	0.5943	0.4646	0.7274
2 vs. 3	0.2891	0.1018	0.3449	0.0249	0.1715
3 vs. 4	0.1394	0.0015	0.4780	0.1420	0.0018
Position					
Upper	78a	223a	270a	94.00a	567a
Lower	50a	50b	263a	95.02a	365b
Side					
North	63a	148a	255a	98.07a	468a
South	65a	125a	278a	90.95a	464a
ANOVA P-Value					
Treatment (T)	0.0931	0.0055	0.5200	0.0280	0.0183
Position (P)	0.4088	<0.0001	0.9000	0.9482	0.0164
Side	0.9400	0.5591	0.7063	0.6498	0.9636
T x P	0.8396	0.0181	0.6855	0.3367	0.0879

[z] Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Like blossom clusters, fruit set on older branch sections was not influenced by hedging alone. Fruit set was higher for TW DH+SH+RP than TW DH+SH for only the 2019 branch section. Compared to no hedging (TW), the combination of dormant plus summer hedging (TW DH+SH) did not increase fruit set on any branch section. Total fruit set per branch was about 35% lower on hedged trees (TW DH+SH) than on nonhedged trees (TW). Final fruit set in 2021 was not affected by tree side, and fruit set was higher for the upper canopy for the 2019 branch section and for the total branch (Table 6).

‘Fuji’ is a tip-bearer (Swenson, 2002) and the dormant hedging likely removed many of the terminal flower buds and summer hedging may have removed some of the terminal fruits, explaining the lower final fruit set values for 2020 wood. Mika et al. (2016) found hedging to decrease yield per tree in the first year with no influence the next two years. In our study, TW DH+SH had lower total fruit set whereas TW DH+SH+RP had the highest fruit set. In a narrow tree wall, hedging alone decreased total fruit set when compared to non-hedged trees. With the hedging blades removing potential fruiting wood during summer, this does not come as a surprise, although the most significant difference was seen on 2019 wood, where the hedger would not have reached. Lewis (2018) states the promotion of flowering on blind wood near the trunk as one of the main hedging benefits, but these data contradict that statement. Root pruning, conversely, improved fruit set on all branch sections when separated by year. Detailed data for flowering and fruiting on wood of various branch sections are available to compare our results, but there is a clear indication that root pruning, not hedging, positively affected flowering and fruiting on wood near the trunk.

Fruit Quality.

Table 7. 'Fuji' fruit quality characteristics in 2021 as influenced by three methods of converting tall spindle trees to tree walls.

Treatment[z]	Starch index	Blush (% red)	Firmness (N)	Soluble Solids (%)	Fruit per tree	Yield (Kg/tree)	Fruit wt. (g)
1 TS	6.9	47.7	7.9	16.1	34.2	8.4	250.99
2 TW	6.8	44.1	8.0	16.6	44.1	10.1	230.85
3 TW+DH+SH	6.8	43.8	7.7	15.2	60.9	12.8	225.17
4TW+DH+SH+RP	6.5	55.0	7.6	15.1	55.8	11.0	203.55
Contrast P-Values							
1 vs. 2	0.2615	0.3010	0.6185	0.1267	0.2016	0.1733	0.1816
2 vs. 3	0.2399	0.9217	0.0489	0.0002	0.0342	0.0252	0.7029
3 vs. 4	0.5183	0.0072	0.3456	0.7339	0.5108	0.1332	0.1527
ANOVA P-Value							
Treatment (T)	0.3318	0.0194	0.0187	0.0001	0.0060	0.0066	0.0266

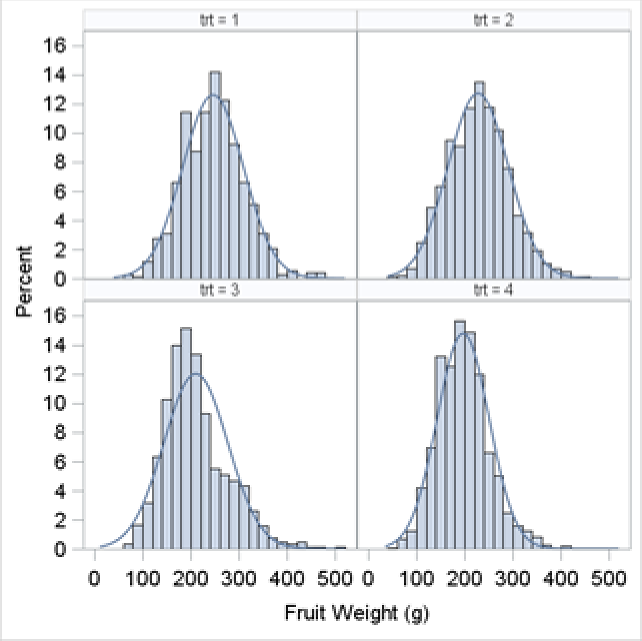
[z] Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

In general, treatments had little effect on fruit size or fruit quality characteristics (Table 7). Starch index was not affected by treatment. Fruit red blush was not enhanced by converting from the tall spindle form to the tree wall with no hedging (TS vs. TW) or by hedging (TW vs. TW DH+SH). Compared to hedged trees (TW DH+SH), trees that were hedged and root pruned (TW DH+SH+RP) had greater percentage of fruit surface with red blush. Fruits from nonhedged trees (TW) were slightly firmer and had higher soluble solids than fruits from trees that were hedged (TW DH+SH). Tree walls that were hedged (TW DH+SH) had more fruit per tree and higher yield than tree walls that were not hedged (TW). Mean fruit weight was highest for tall spindle trees, but conversion to a tree wall with or without hedging or root pruning did not influence fruit weight.

Barden and Marini (1984) found summer heading all terminal shoots on vigorous trees reduced soluble solids levels and increased red fruit surface color, which is consistent with our results, and Schupp and Ferree (1984) found root pruning increased soluble solids in two of three years. Emerson and Hayden (1984) found hedging peach trees in winter and summer did not affect yield but hedging improved red fruit peel color. Autio and Greene (1990) found that summer thinning cuts improved red fruit coloring of ‘McIntosh’ apples. They noticed a reduction in preharvest fruit drop. Marini et al. (1993) found that annual dormant heading of the leader and terminal shoots reduced cumulative yield of young trees due to bud removal by pruning and stimulation of growing points to develop into shoots rather than spurs. This difference could be cultivar-dependent, with ‘Fuji’ being a tip-bearer (Swenson, 2002). Tip-bearing cultivars could benefit from improved shoot numbers where flowers are borne on shoot tips. Dormant and summer hedging could remove the flower buds developed in the growing season, although results show fruit number and yield increased with hedging (Table 7). The number of fruits removed by hedging were not counted.

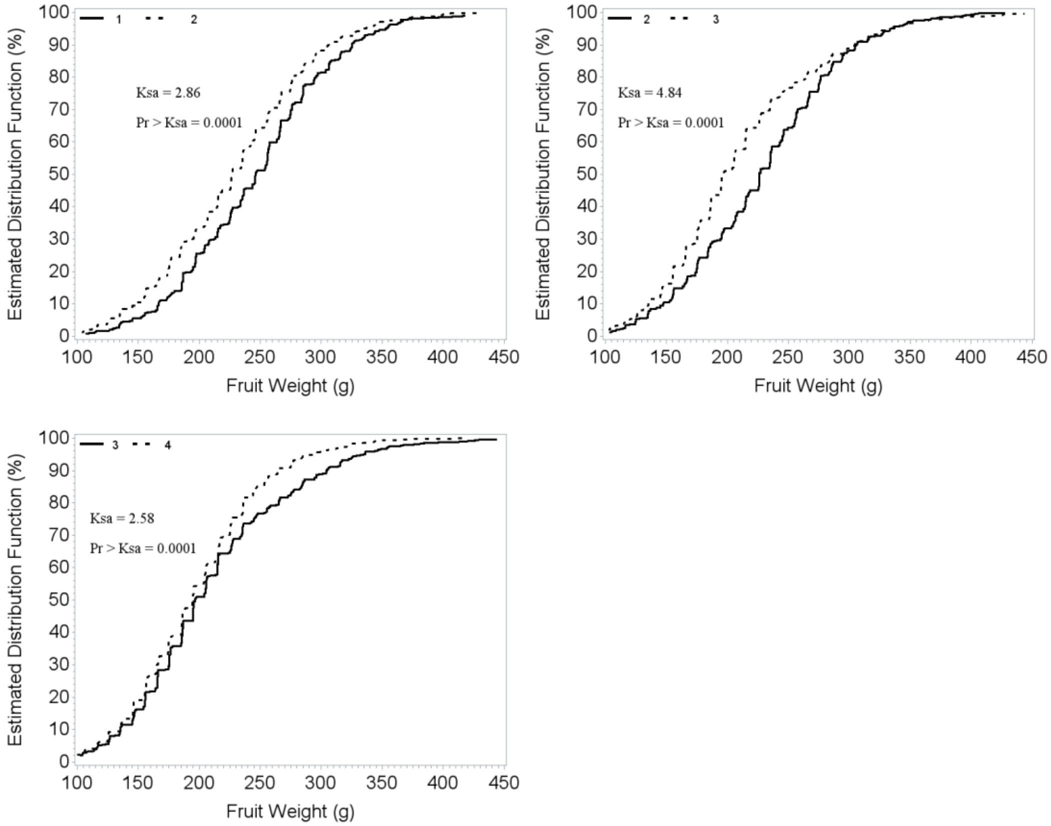
Ferree and Rhodus (1993) found hedging and root pruning decreased yield, with root pruning causing the greatest reduction in yield. Robinson et al. (2013) found summer hedging caused a nonsignificant reduction in yield and crop value and a nonsignificant improvement in fruit color, unlike our results. Mika et al. (2016) had the results most like our study, where hedging increased yields but decreased fruit size and mean fruit weight. Mika et al. (2016) also found a decrease in area of red blush with hedging, potentially due to tree crowding and poor light penetration into the canopy. In our study, hedging improved red blush significantly only when coupled with root pruning, but hedging also reduced soluble solids.

Figure 2. Fruit weight distribution from four treatments^{z}.



^{z} Treatments: 1 = tall spindle + no hedging (TS), 2 = tree wall + no hedging (TW), 3 = tree wall + dormant & summer hedging (TW DH+SH), 4 = tree wall + dormant & summer hedging plus root pruning (TW DH+SH+RP).

Figure 3. Estimated cumulative empirical distribution functions (EDF) for ’Fuji’ fruit weights of fruits harvested from different treatments. The EDFs for three combinations of treatments were compared with Kolmogorov-Smirnov two-sample test and the test statistic (Ksa) and P-value associated with the test are presented in each figure.

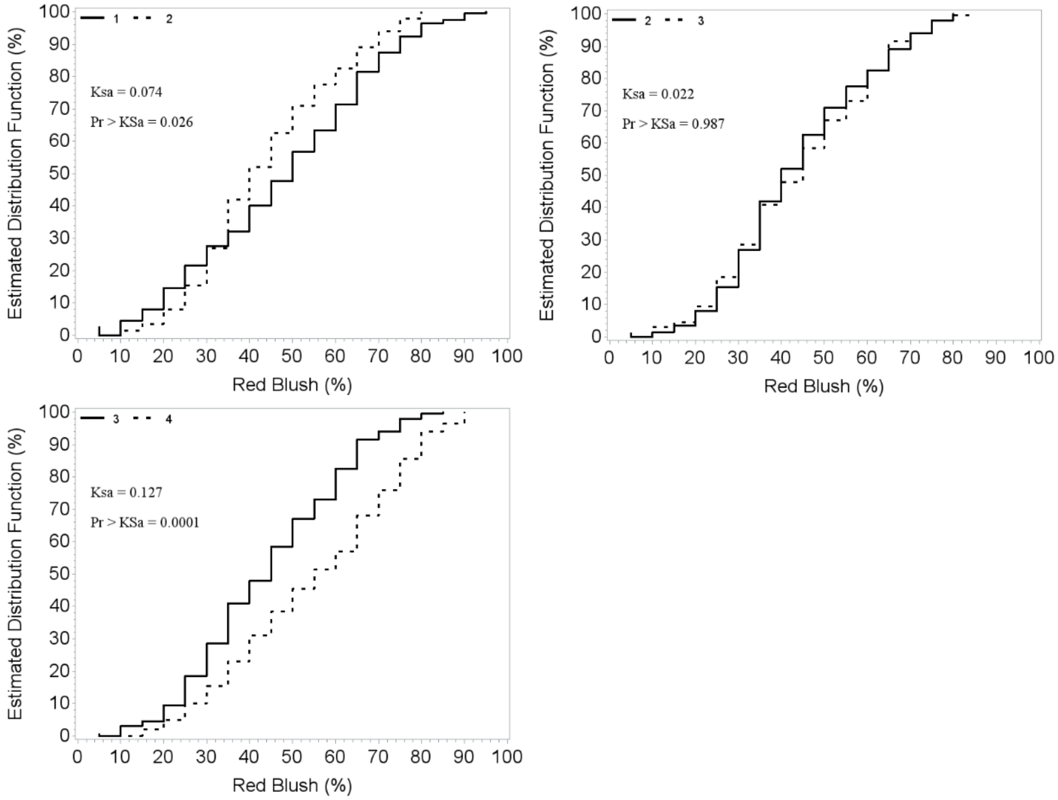


Fruit weight in Fig. 2 was normally distributed for the treatments that were not hedged (TS and TW), but not for the treatments that were hedged (TW DH+SH and TW DH+SH+RP). Distributions with skewness coefficients less than -0.5 or greater than 0.5 are generally considered skewed. Therefore, TW DH+SH is skewed to the left and TW DH+SH+RP is sightly skewed to the right. For all treatments the value of kurtosis was less than 3.0, indicating that all histograms have short tails, and most observations are tightly clustered around the mean. Since the distribution of fruit weights for hedged treatments were skewed to the left, this indicates that hedged trees produced more small fruits.

The estimated cumulative empirical distribution functions (EDF) in Fig. 3 for all three pair-wise comparisons were significantly different (P=0.0001) (Fig. 3). TS had more large fruit than TW, TW had more large fruit than TW DH+SH, and TW DH+SH had more large fruit than TW DH+SH+RP. Based on the EDF's, 50% of the fruits were larger than 246g, 226g, 196g and 194g for TS, TW, TW DH+SH and TW DH+SH+RP, respectively. Hedging decreased fruit size, consistent with Mika et al. (2016). Root pruning also decreased fruit size, seen previously by Schupp et al. (1992). Smaller fruit size caused by hedging and root pruning is important because fruit value often increases with fruit size for both fresh market and processing apples.

Ease of harvesting should be considered when creating narrow tree walls in commercial orchards. Although narrow canopies facilitate visualization of the fruits, current hedging recommendations result in multiple stubs on the tree periphery. These stubs are dangerous for individuals harvesting the fruit and may result in cuts and scrapes on the arms and body, making harvesting conditions less safe and possibly increasing harvest times. This study did not evaluate the amount of time to harvest hedged vs. non-hedged trees, but this type of information may be useful to growers looking to implement hedging in their orchard.

Figure 4. Estimated cumulative empirical distribution functions (EDF) for ‘Fuji’ red blush percentage of fruits harvested from different treatments. The EDFs for three combinations of treatments were compared with Kolmogorov-Smirnov two-sample test and the test statistic (Ksa) and p-value associated with the test are presented in each figure.



The distributions for red blush for TS and TW were different at the 0.026 % level of significance (Fig. 4). The distributions for red blush TW and TW DH+SH were not different (P=0.987), but the distributions for red blush for TW DH+SH and TW DH+SH+RP were different at the 0.0001% level of significance (Fig. 4).

Table 9. Percentage of ‘Fuji’ fruit with less than a given red blush as affected by heading and root pruning in 2021.

Fruit (%) with less than 40, 50, 60, and 70 percent of red blush				
Treatment	<40	<50	<60	<70
1 Tall Spindle (TS)	40	57	71	87
2 Tree Wall (TW)	52	71	82	94
3 Tree Wall + Dormant Hedging + Summer Hedging (TW DH+SH)	48	67	82	94
4 Tree Wall + Dormant Hedging + Summer Hedging + Root Pruning (TW DH+SH+RP)	31	46	57	76

Treatment 4 (TW DH+SH+RP) had the most fruit with the highest percentage of red blush (Table 9). Treatment 3 (TW DH+SH) did not improve fruit red color when compared to other treatments. Although grade standards are subjective, some supermarkets require 55% red on ‘Fuji’ for fancy fruit and 66% red for extra fancy fruit (M. Boyer, personal communication, March 20, 2022). Treatment 4 (TW DH+SH+RP) produced the largest percentage of fruit in the fancy and extra fancy categories. The combination of dormant and summer hedging did not improve red fruit color (Table 7, Table 9).

Conclusions. Transition from tall spindle training systems to a narrow tree wall through hedging and root pruning produced mixed results. While light levels were increased slightly by hedging and root pruning, the increase could partly be attributed to the method of measuring light and was still much lower than necessary to have a significant impact on leaves and fruit. Specific leaf weight values confirmed that differences in light levels between treatments were not enough to impact leaves in the outer or inner canopy.

Shoot growth was not suppressed the season following hedging unless hedging was combined with root pruning. Hedging increased yields, but the percentage of poorly colored fruit increased, and highly colored fruit decreased. Fruit size and soluble solids concentrations also suffered with hedging. While root pruning increased fruit color and yield, a significant decrease in fruit size was noted, possibly yielding fruit that fail to make certain grade standards. Based on our results, slender spindle trees can be converted to tree walls with dormant pruning, but dormant plus summer hedging has little effect on vegetative growth, flowering, yield, or fruit quality.

LITERATURE CITED

Andrews, R. E. & E. I. Newman. 1968. The influence of root pruning on the growth and transpiration of wheat under different soil moisture conditions. New Phytol. 67:617.

Arakawa, O., Y. Hori & R. Ogata. 1985. Relative effectiveness and interaction of untraviolet-B, red and blue light in anthocyanin synthesis of apple fruit. Physiol. Plant. 64(3):323-327.

Atkinson, D. 1980. The distribution and effectiveness of the roots of tree crops. Hort. Rev. 2:424-490.

Autio, W. R. & D. W. Greene. 1990. Summer Pruning Affects Yield and Improves Fruit Quality of `McIntosh' Apples. Jour. Amer. Soc. Hort. Sci., 115(3):356–359. https://doi.org/10.21273/jashs.115.3.356

Awad, M., P. Wagenmakers & A. Jager. 2001. Effect of light on flavonoid and chlorogenic acid levels in the skin of 'Jonagold' apples. Sci. Hort. 88:289-298.

Bastías, R. M. & L. Corelli-Grappadelli. 2012. Light quality management in fruit orchards: physiological and technological aspects. Chil. Jour. Ag. Res., 72(4):574–581. https://doi.org/10.4067/s0718-58392012000400018

Barden, J. A. 1974. Net photosynthesis, dark respiration, specific leaf weight, and growth of young apple trees as influenced by light regime. J. Amer. Soc. Hort. Sci. 99:547-551.

Barden, J. A. & R. P. Marini. 1984. Summer and dormant pruning of apple – a four year summary. Acta Hortic. 146:263-268.

https://doi.org/10.17660/ActaHortic.1984.146.30

Barden, J. A. & R. P. Marini. 1998. Growth and cropping of young apple trees as affected by heading and support of the central leader. HortSci. 33:39-41.

Barden, J. A. & R. P. Marini. 2001. Yield, fruit size, red color, and estimated crop value in the NC-140 1990 cultivar/rootstock trial in Virginia. J. Amer. Pomol. Soc. 55:154-158.

Barritt, B. H., J. A. Barden, J. Cline, R. L. Granger, E. E. Hoover, M. M. Kushad, R. P. Marini, M. Parker, R. L. Perry, T. Robinson, C. R. Unrath & M. A. Dilley. 1997. North American NC-140 Apple Orchard Systems Trial. Acta Hortic. 451:443-452. https://doi.org/10.17660/ActaHortic.1997.451.50

Blanpied, G. D. & K. J. Silsby. 1992. Predicting harvest date windows for apples. I. B. 221. Cornell Coop. Ext. Pub.

Brevedan, E. R. & H. F. Hodges. 1978. Effects of moisture deficits on C translocation in corn (Zea mays L.). Plant Physiol. 52:436-439.

Campbell, R. J., R. P. Marini & J. B. Birch. 1991. Canopy position affects light response curves for gas exchange characteristics of apple spur leaves. J. Amer. Soc. Hort. Sci. 117:467-472.

Campbell, R. J. & R. P. Marini. 1992. Light environment and time of harvest affect `Delicious' apple fruit quality characteristics. Jour. Amer. Soc. Hort. Sci. 117(4):551–557. https://doi.org/10.21273/jashs.117.4.551

Childers, N. F. 1969. Modern fruit science (4th ed.). Horticultural Publications, New

Brunswick, N.J. Print.

Courtney, R. & T. J. Mullinax. 2016. Keeping limbs in line with mechanical pruning. Good Fruit Grower. Retrieved from: https://www.goodfruit.com/keeping-limbs-in-line-with-mechanical-pruning-video/

Crassweller, R. M., K. Peter, G. Krawczyk, J. Schupp, T. Ford, M. Brittingham, J. Johnson, L. LaBorde, J. Harper, K. Kephart, R. Pifer, K. Kelley, L. He, P. Heinemann, D. Biddinger, M. Lopez-Uribe, R. Marini, T. Baugher, D. Weber, L. Kime, E. Crow, E. Weaver, & B. Lehman. 2020. Penn State tree fruit production guide. Publ. AGRS-045. Penn State Extension. https://cdn.ymaws.com/ashs.org/resource/resmgr/extension/Penn_State_Tree_Fruit_Produc.pdf.

Elfving, D. C. 1990. Growth and productivity of 'Empire' apple trees following a single heading-back pruning treatment. HortScience 25:908-910.

Emerson, F. H. & R. A. Hayden. 1984. Control of tree vigor by mechanical hedging. Acta Hortic. 146:231-234.

Fang, C., K. Zhou, Y. Zhang, B. Li, & M. Han. 2017. Effect of root pruning and nitrogen fertilization on growth of young 'fuji' apple (Malus domestica borkh.) trees. J. of Plant Nutrition 40(11):1538-1546. https://doi.org/10.1080/01904167.2016.1240202

Ferree, D. C. 1976. Influence of slotting saw mechanical pruning and alar on apple fruit size and quality. Res. Cir. 220:3-7.

Ferree, D. C. & A. N. Lasko. 1979. Effect of selected dormant pruning techniques in a hedge-row apple orchard. J. Amer. Hort. Sci. 104:736-739.

Ferree, D. C. 1984. Influence of various times of summer hedging on yield and growth of apple trees. Res. Cir. 283:3-7.

Ferree, D. C. & W. T. Rhodus. 1993. Apple tree performance with mechanical hedging or root pruning in intensive orchards. Jour. Amer. Soc. Hort. Sci. 118(6):707–713. https://doi.org/10.21273/jashs.118.6.707

Ferree, D. C. & J. R. Schupp. 2003. Pruning and Training Physiology. In: D.C. Ferree and I. J. Warrington (eds.). “Apples: Botany, Production and Uses”. CABI Publishing, ISBN 0 85199 592 6. Print.

Ferree, D. C. & I. J. Warrington. 2003. Apples: Botany, Production and Uses. CABI Publishing, ISBN 0 85199 592 6. Print https://doi.org/http://dx.doi.org/10.1079/9780851995922.0000

Fioravanço, J. C. & A. B. C. Czermainski. 2018. Biennial bearing in apple cultivars. Plant Prod. 65(2):144-149.

Forshey, C.G. & D.C. Elfving. 1976. Training and pruning apple trees. N.Y. Ext. Info. Bul. 112.

Fumey, D., P. E. Lauri, Y. Guédon, C. Godin & E. Costes. 2011. Effects of pruning on the apple tree: From tree architecture to modeling. Acta Hort. 903:597–602. https://doi.org/10.17660/ActaHortic.2011.903.82

Gandev, S. & V. Dzhuvinov. 2014. Training and Pruning of Apple and Modern Trends of Development – An Overview. Türk Tarım ve Doğa Bilimleri Dergisi-Turk. Jour. of

Ag. Nat. Sci. 1264–1267.

Gardner, V. R. 1917. The winter heading-back and thinning-out of apple shoots in young trees. Ore. Agr. Expt. Sta. Bul. 146:57-78.

Geisler, D. & D. C. Ferree. 1984. Response of plants to root pruning. Hort Rev. 6:155-188.

Glenn, D. M. & S. S. Miller. 2005. Effects of apogee on growth and whole-canopy photosynthesis in spur 'Delicious' apple trees. HortScience 40(2):397–400. https://doi.org/10.21273/hortsci.40.2.397

Gönen, M. 2006. Receiver operating characteristic (ROC) curves. Proc. NE SAS User Group Conf. Philadelphia, PA. https://www.lexjansen.com/nesug/nesug06/an/da11.pdf, accessed 19 July 2021.

Greene, D. W. & W. R. Autio. 1994. Notching techniques increase branching of young apple trees. J. Amer. Hort. Sci. 119(4):678-682.

Hampson, C. R., H. A. Quamme & R. T. Brownlee. 2002. Canopy growth, yield, and fruit quality of "Royal Gala" apple trees grown for eight years in five tree training systems. HortScience 37(4):627–631. https://doi.org/10.21273/hortsci.37.4.627

Hansen, C. M., R. P. Larsen & G. Monroe. 1968. Hedge pruning fruit trees. Mich. Agri. Exp. Sta. Quart. Bull. 50:331-341.

Harper, J. K., A. J. Jimenez-Maldonado, R. M. Crassweller & D. E. Smith. 2013. Impact of producer risk preferences on selection of fresh-market apple training systems. Inter. J. Fruit Sci. 13(3):265-273. https://doi.org/10.1080/15538362.2012.679179

Hayden, R. A. & F. H. Emerson. 1976. It pays to hedge. Amer. Fruit Grower 96(11):11-12.

He, L & J. R. Schupp. 2018. Sensing and automation in pruning of apple trees: a review. Agronomy 8(10):211. https://doi.org/10.3390/agronomy8100211

Head, G. C. 1967. Effects of seasonal changes in shoot growth on the amount of unsuberized root on apple and plum trees. J. Hort. Sci. 42:169-180.

Heinicke, D. R. 1963. The micro-climate of fruit trees. I. Light measure-ments with uranyl oxalate actinometer. Can. J. Plant Sci. 43:561-568.

Heinicke, D. R. 1966. Characteristics of McIntosh and Red Deliciousapples. as influenced by exposure to sunlight during the growing season. Proc. Amer. Soc. Hort. Sci. 89:10-13.

Heinicke, D. R. 1975. High-density apple orchards – planning, training, and pruning. Agri. Handb. 458:1-36.

Hosmer, D.W. & S.L. Lemeshow. 2000. Applied Logistic Regression. 2nd Edition. John Wiley and Sons, Inc. New York, NY.

Howlett, F. S. 1970. Status of apple cultivars for Ohio apple production. Hort. Mimeo. Series No. 335A.

Jackson, J. E. 1980. Light interception and utilization by orchard systems. Hort. Rev. 2:208-267.

Jackson, J. E., J. W. Palmer, M. A. Perring & R. O. Sharples. 1977. Effects of Shade on the Growth and Cropping of Apple Trees. III. Effects on Fruit Growth, Chemical

Composition and Quality at Harvest and After Storage. J. Hort. Sci. 52(2):267-282.

Ju, A., Y. Duan, & Zh. Ju. 1999. Effects of covering the orchard floor with reflecting films on pigment accumulation and fruit coloration in ‘Fuji’ apples. Sci. Hort. 82:47-56.

Kappel, F. & H. A. Quamme. 1993. Orchard training systems influence early canopy development and light microclimate within apple tree canopies. Can. J. Plant Sci. https://doi.org/10.4141/cjps93-038

Kiernan, K. 2018. Insights into using the GLIMMIX procedure to model categorical outcomes with random effects. SAS Global forum proc. Paper SAS2179-2018. https://www.sas.com/content/dam/SAS/support/en/sas-global-forum-proceedings/2018/2179-2018.pdf, accessed 19 July 2021.

Kolomiev, I. A. 1976. Surmounting of periodicity of bearing in the apple. Kiev, Urozaj:17-50.

Koutinas, N., G. Pepelyankov & V. Lichev. 2010. Flower induction and flower bud development in apple and sweet cherry. Biotech. & Biotech. Devel. 24(1):1549-1558. https://doi.org/10.2478/V10133-010-0003-9

Layne, D. 2001. Tree fruit reflective film improves red skin coloration and advances maturity in peach. HortTechnology 11:234-242.

Lespinasse, J. M. 1980. La conduite du pommier. II. – L’axe vertical. La rénovation de verges. INVUFLEC, Paris, 120 pp.

Lewis, K. 2018.. Mechanical Hedging in Apples. WSU Ext., Retrieved from http://treefruit.wsu.edu/article/mechanical-hedging-in-apples/

Lord, W. J. & J. Costante. 1977. Establishment and management of compact apple trees: Part 3. Mass. Agr. Ext. Serv. Fruit Notes 42(2):15-28.

Marini, R. P. & J. A. Barden. 1981. Seasonal correlations of specific leaf weight to net photosynthesis and dark respiration of apple leaves. Photosynthesis Res. 2:251-258.

Marini, R., & J. A. Barden. 1982. Effects of Summer vs. Dormant Pruning and NAA Treatment on Growth of One- and Two-year-old Apple Trees. J. Amer. Soc. Hort. Sci. 107(4):604-607.

Marini, R. P. & J. A. Barden. 1982a. Light penetration on overcast and clear day, and specific leaf weight in apple trees as affected by summer or dormant pruning. J. Amer. Soc. Hort. Sci. 107:39-43.

Marini, R. P. & J. A. Barden. 1982b. Net photosynthesis, dark respiration, transpiration, and stomatal resistance of young and mature apple trees as influenced by summer or dormant pruning. J. Amer. Soc. Hort. Sci. 107:170-174.

Marini, R. P. & J. A. Barden. 1982c. Growth and flowering of vigorous apple trees as affected by summer or dormant pruning. J. Amer. Soc. Hort. Sci. 107:34-39.

Marini, R. P. 1986. Defoliation, flower bud cold hardiness, and bloom date of peach as influenced by pruning treatments. J. Amer. Soc. Hort. Sci. 113:391-394.

Marini, R. P. & D. L. Sowers. 1990. Net photosynthesis, specific leaf weight, and flowering of peach as influenced by shade. HortSci. 25(3):331-334.

Marini, R. P., J. A. Barden & D. Sowers. 1993. Growth and Fruiting Responses of `Redchief Delicious' Apple Trees to Heading Cuts and Scaffold Limb Removal. Journal of the Amer. Soc. Hort. Sci. 118(4):446–449. https://doi.org/10.21273/jashs.118.4.446

Marini, R.P. & J. A. Barden. 2004. Yield, fruit size, red color, and a partial economic analysis for 'Delicious' and 'Empire' in the NC-140 1994 systems trial in Virginia. J. Amer. Pomol. Soc. 58:4-11.

Marini, R. P., J. L. Anderson, W. R. Autio, B. H. Barritt, J. Cline, W. P. Cowgill, Jr., R. C. Crassweller, R. M. Garner, A. Gauss, R. Godin, G. M. Greene, C. Hampson, P. Hirst, M. M. Kushad, J. Masabni, E. Mielke, R. Moran, C. A. Mullins, M. Parker, R. L. Perry, J. P. Privé, G. L. Reighard, T. Robinson, C. R. Rom, T. Roper, J. R. Schupp, E. Stover & R. Unrath. 2006. Performance of 'Gala' apple trees on 18 dwarfing rootstocks: ten-year summary of the 1994 NC-140 rootstock trial. J. Amer. Pom. Soc. 60(2):69-83.

Marini, R. P. 2020. Training and pruning apple trees. Virg. Coop. Ext. Pub. 422-021:1-9.

McArtney, S. J. & R. P. Belton. 1992. Apple shoot growth and cropping responses to root pruning. New Zeal. Jour. Crop Hort. Sci. 20(4):383–390. https://doi.org/10.1080/01140671.1992.10418054

Mika, A., Z. Buler & W. Treder. 2016. Mechanical pruning of apple trees as an alternative to manual pruning. Acta Hort. 15(1):113–121.

Milkovich, M. 2020. Mediterranean modernization. Good Fruit Grower, Retrieved from https://www.goodfruit.com/mediterranean-modernization/

Milliken, G.A. & D. E. Johnson. 2002. Analysis of messy data. Vol. III: Analysis of covariance. Chapman and Hall/CRC, New York, NY.

Mitre, V., I. Mitre, A. F. Sestras & R. E. Sestras. 2012. Effect of Roots Pruning upon the Growth and Fruiting of Apple Trees in High Density Orchards. Bulletin of Univ. of Ag. Sci. and Vet. Med. Cluj-Napoca - Horticulture 69(1):254–259. https://doi.org/10.15835/buasvmcn-hort:8527

Park, S. H., J. M. Goo & C. H. Jo. 2004. Receiver operating characteristic (ROC) curve: practical review for radiologists. Korean J. Radiol. 5:11-18. https://doi.org/10.3348/kjr.2004.5.1.11

Preston, A. P. & M. A. Perrin. 1974. The effect of summer pruning and nitrogen on growth, cropping and storage quality of Cox's Orange Pippin apple. Jour. Hort. Sci. 49(1):77–83. https://www.tandfonline.com/doi/pdf/10.1080/00221589.1974.11514553?needAccess=true

Randolph, W. S. & C. Wiest. 1981. Relative importance of tracable factors affecting the establishment of transplanted holly (Ilex crenata). J. Amer. Hort. Sci. 106:207-210.

Robinson, T. L., A. L. Lakso & Z. Ren. 1991. Modifying apple tree canopies for improved production efficiency. HortSci. 26(B):1005-1012.

Robinson, T. L., Hoying, S. A. & G. H. Reginato. 2006. The tall spindle apple production system. New York Fruit Quar. 14(2):21-27.

Robinson, T. L., M. Sazo, S. A. Hoying, L. Dominguez & J. C. Fachinello. 2013. The effect of summer hedging of tall spindle apple trees on growth, fruit quality, and flowering. ASHS.

Robinson, T. L., S. Hoying, M. Sazo, A. DeMarree & L. Dominguez. 2013a. A vision for apple orchard systems of the future. N.Y. Fr. Quar. 21(3):11–16.

Rom, C. R. 1982. Pruning apple roots at planting. Arkansas Farm Res., July-Aug. 5 pp.

Rom, R. C. & R. F. Carlson. 1987. Rootstocks for fruit crops. New York: Wiley. Print.

Rom, C. R. 1991. Light thresholds for apple tree canopy growth and development. HortSci. 26(8):989-992.

Rosecrance, R., L. Milliron & F. Niederholzer. 2021. Mechanical Pruning of Prune Trees Update 2021. Univ. of Cal. Ag. and Nat. Res. https://www.sacvalleyorchards.com/prunes/horticulture-prunes/mechanical-pruning/

Sagong, D. H. & T. M. Yoon. 2015. Optimum crop load in different planting densities of adult 'Fuji'/M.9 apple tree for preventing biennial bearing and stabilizing tree Vigor. Kor. Jour. Hort. Sci. Tech. 33(1):1–10. https://doi.org/10.7235/hort.2015.13126

Saure, M. C. 1987. Summer Pruning Effects in Apple – a Review. Sci. Hort. 30:253-282.

Schumacher, R. 1975. Einfluss des Wurzelschnittes auf die Fruchbarkeit von Apfelbaumen. Schweiz. Zeitschr. Obst. Weinbau 111(5):115-116.

Schupp, J. R. & D. C. Ferree. 1987. Effect of root pruning at different growth stages on growth and fruiting of apple trees. HortSci. 22:387-390.

Schupp, J. R. & D. C. Ferree. 1988. Effects of root pruning at four levels of severity on growth and yield of ‘Melrose’/M.26 apple trees. J. Amer. Hort. Sci. 113(2):194-198.

Schupp, J. R. & D. C. Ferree. 1990. Influence of time of root pruning on growth, mineral nutrition, net photosynthesis and transpiration of young apple trees. Sci. Hort. 42:299-306.

Schupp, J. R., D. C. Ferree & I. J. Warrington. 1992. Interactions of root pruning and deblossoming on growth, development and yield of ‘Golden Delicious’ apple. Jour. Hort. Sci. 67:465–480. https://doi.org/https://doi.org/10.1080/00221589.1992.11516272

Schupp, J. R., H. E. Winzeler, T. M. Kon, R. P. Marini, T. A. Baugher, L. F. Kime & M. A. Schupp. 2017. A method for quantifying whole-tree pruning severity in mature tall spindle apple plantings. HortSci. 52(9):1233–1240. https://doi.org/10.21273/HORTSCI12158-17

Shin, S. & B. Coulter. 2009. ROC analysis for the evaluation of continuous biomarkers: existing tools and new features in SAS® 9.2. Proc. 34th Annu. SAS® Users Groups Intl. Conf. https://www.lexjansen.com/pharmasug/2009/sp/SP09.pdf , accessed 20 July 2021.

Tukey, H. B. 1964. Dwarfed fruit trees, for orchard, garden and home. New York, Macmillan. Print.

Uselis, N., J. Viškelis, J. Lanauskas, M. Liaudanskas, V. Janulis & D. Kviklys. 2020. Effects of growth control on yield and fruit quality of the apple cultivar ‘rubin.’ Ag. and Food Sci. 29(3):245–252. https://doi.org/10.23986/afsci.90757

Utermark, H. 1977. Summer pruning to control growth and maintain fruiting in mature apple trees. Comp. Fruit Trees 10:86-90.

Vercammen, J., G. v. Daele & A. Gomand. 2005. Root pruning: a valuable alternative to reduce the growth of 'Conference'. Acta. Hort. 671:74. https://doi.org/10.17660/ActaHortic.2005.671.74

Wallis, A. E., M. R. Miranda-Sazo & K. D. Cox. 2021. Assessing and minimizing the development and spread of fire blight following mechanical thinning and pruning in apple orchards. Pl. Dis. 105(3):650–659. https://doi.org/10.1094/PDIS-06-20-1324-RE

Webster, A. D., C. J. Atkinson, S. J. Vaughan & A. S. Lucas. 1997. Controlling the shoot growth and cropping of sweet cherry trees using root pruning or root restriction techniques. Acta. Hort. 451:643-652. https://doi.org/10.17660/ActaHortic.1997.451.76

Wertheim, S. J. 1968. The training of the slender spindle. Proef. Fruit. No. 37, Wilhelmindadorp, The Netherlands, 37 pp.

Yang, S., S. Xing, C. Liu, Z. Du, H. Wang & Y. Xu. 2010. Effects of root pruning on the vegetative growth and fruit quality of Zhanhuadongzao trees. HortSci. 37:14-21.

Zhang, X., L. He, J. Zhang, M. D. Whiting, M. Karkee & Q. Zhang. 2020. Determination of key canopy parameters for mass mechanical apple harvesting using supervised machine learning and principal component analysis (PCA). Biosys. Eng. 193:247-263. https://doi.org/10.1016/j.biosystemseng.2020.03.006