A Review

Regulating Vegetative Growth in Deciduous Fruit Trees

Stephen S. Miller and Thomas Tworkoski

United States Department of Agriculture, ARS,
Appalachian Fruit Research Station,
45 Wiltshire Road, Kearneysville, WV 25430

INTRODUCTION

The desire to regulate excessive vegetative (shoot) growth and maintain a smaller deciduous fruit tree is not new (Hugard, 1980; Walker, 1980). Ancient gardeners and modern fruit growers have used scoring and girdling, dwarfing rootstocks, pruning, and/or limb positioning techniques to reduce or regulate growth.

The need to regulate growth is based on several factors. Of significance is the relationship between growth and fruiting. Excessive vegetative growth reduces flowering and ultimately fruiting (Forshey and Elfving, 1989; Luckwill, 1970). While a certain amount of growth is necessary to maintain vigor and a healthy fruiting mantle (bearing canopy) with an adequate leaf surface, the ultimate goal of the fruit grower is to produce fruit, not leaves and wood. The move to higher density, more efficient orchard systems has also been an important factor in the transition to smaller trees and a need to regulate growth. The desire by today's orchardist to obtain early cropping and to reduce labor inputs necessitates smaller trees planted in high-density systems.

In the early life of an orchard, growth is desirable in order to fill the tree's allotted space and to provide for an adequate support framework for later fruit production. Modern high-density orchards, however, are designed to move quickly from the juvenile vegetative phase to a reproductive or fruiting phase (Luckwill, 1970). This situation often presents a problem. How does the tree fruit grower reduce vegetative growth without adversely impacting the vigor and productivity of the tree? In the bearing orchard, excessive growth often leads to: overcrowding and reduced light penetration into the canopy, a need for additional pruning, poorer fruit quality, and increased pest problems. These problems are accentuated in a high-density orchard where trees are closely spaced. In addition, there is often a greater need for vegetative growth control as trees age.

The volume of literature dealing with growth control and the factors that regulate growth in fruit trees is quite large and well beyond the scope of this review. Recent reviews have focused on chemical methods of growth control (Martin, 1979; Miller, 1988; Quinlan, 1982; Williams, 1984). The current review will briefly examine each of the various ways in which growth may be regulated thereby providing the reader with a broader understanding of the techniques for growth regulation in deciduous tree fruits. In this review, the discussion of chemical growth control will emphasize work since the last comprehensive reviews (Davis and Curry, 1991; Miller, 1988). This is not an exhaustive discussion on the physiology of growth regulation, but through references, the intent is to provide the reader with sufficient resources for additional information in this area of growth control.

Vegetative growth may be regulated genetically, environmentally, or by various cultural techniques. This review will emphasize cultural techniques that can be used to control vegetative growth with only a brief discussion of the genetic and environmental factors regulating growth. For the purposes of this review growth is characterized as extension shoot growth, trunk cross sectional area [which is strongly correlated with tree size (Barden and Marini, 2001; Layne et al., 1976; Westwood and Roberts, 1970), or tree volume based on canopy height and width. Research with apple [*Malus sylvestris* (L.) Mill. Var. *domestical* (Burkh.) Mansf.], peach [*Prunus persica* (L.) Batsch.], pear (*Pyrus communis* L.), and cherry (*Prunus avium* L. and *P. cerasus* L.) will be emphasized to illustrate the methods by which growth is regulated in deciduous fruit crops.

Genetic control of growth and tree size

Within a population of hybridized fruit trees of the same species a broad range of growth habits exists, resulting in trees of various shapes and sizes (Schmidt and Gruppe, 1988). Trees are characterized as dwarf, semi-dwarf, or compact (also called spurred) depending on their size relative to a standard wild type or representative size tree. Natural or planned hybridization has resulted in trees of reduced stature and growth in all the commercially important deciduous tree fruit crops (Frecon, 1981; Scorza, 1988; Tukey, 1964). Genetic control of fruit tree growth may occur in the scion, the rootstock, or the interstock of grafted trees. Faust (1989) identified four genetic characters that determine tree size: internode length, branch angle, the location of branching (basitonic, acrotonic, etc.), and the rate of shoot growth or vigor of the tree. Shortened internodes are often the primary characteristic associated with dwarfed trees (Scorza, 1984; Westwood and Zielinski, 1966), but not all dwarfed trees exhibit shortened internodes and most fruit tree species exhibit some or all of the other characters identified by Faust among their progeny (Faust and Zagaja, 1984). Quinlan and Tobutt (1990) provided a brief review of the efforts to genetically develop smaller trees with improved tree structure.

Early efforts to genetically manipulate fruit tree size focused more on rootstocks than selecting scion cultivars with reduced vigor (Trajkovski, 1986). In recent years plant breeders have shown interest in scion vigor and have selected trees with reduced shoot growth and a more compact growth habit (Frecon, 1981; Janick and Moore, 1996; Scorza, 1984, 1987; Trajkovski, 1986). A natural mutation (bud sport) with spur character was first recognized in apple in 1921 in Omak, Washington, but the fruit was not exceptionally attractive and the strain was not widely planted (Fisher and Ketchie, 1981; Maas, 1970). A large number of apple spur mutants were discovered beginning in the 1950's, the most notable being the 'Starkrimson Delicious' (Maas, 1970). These spur-type trees are about two-thirds the size of the standard parent tree, had a large number of spur shoots and a limited number of lateral shoots or extension growth. Natural mutations have resulted in a number of commercially important spur-type apple selections with reduced tree size among several apple cultivars since the late 1950's, most commonly in 'Delicious', 'Golden Delicious', 'Mcintosh', and 'Rome' (Fisher, 1969; Oberle, 1965), but also in other cultivars (Kilpatrick, 1964).

Natural mutations and efforts by plant breeders with peach, pear, cherry, apricot (*Prunus armeniaca* L.), and plum (*Prunus domestica*) have resulted in a number of genetic dwarfs (Fideghelli et al., 1984; Frecon, 1981), but these species have enjoyed less

commercial success than apple, especially in the U.S. The 'Com-Pact Redhaven' peach is an exception as a mutation that has achieved some commercial success (Van Well, 1974), although it, like many other dwarfed tree fruits, has found greater popularity in the home or ornamental garden. Many of these first generation dwarfed trees are now being used as parents to produce dwarfed progeny with improved attributes such as fruit quality, cold hardiness, and pest resistance that were lacking in the parents (Janick and Moore, 1996; Trajkovski, 1986). Peach and cherry breeders have made a special effort in recent years to develop tree growth habits with reduced stature adapted to high density planting systems (Bassi and Rizzo, 2000; Brown et al., 1996; Fideghelli et al., 1984; Scorza, 1988; Scorza et al., 2000; Trajkovski, 1986). Scorza (1988) identified six distinct peach growth habits with reduced tree size. Among these types, pillar (columnar) and upright (standard x pillar) form trees appear to have the greatest potential for adapting to high-density plantings (Scorza et al., 2000). Spur-type trees, as a means of growth control, continue to command attention among breeders, especially in peach (Scorza, 1987; Scorza et al., 2000).

Genetic manipulation to develop tree fruit cultivars with reduced stature continues to show great promise as a means toward efficient high-density plantings. The development of high quality, pest resistant fruiting material could lead to significant advances in fruit production that have not been achieved with rootstocks for many of the deciduous fruit tree species. While rootstocks continue to provide the major source of tree size control for apple, additional efforts to develop scion cultivars with natural growth control could also have significant impact in commercial fruit production.

Environmental control of growth and tree size

Environmental factors (light, temperature, moisture, etc.) regulate plant metabolic processes and thus impact virtually all aspects of plant growth and development. In general, manipulating these factors is not practical as a method for controlling growth in fruit trees. The use of deficit irrigation in arid climates is an exception that will be discussed in more detail later in this review.

Light quantity and quality has a significant effect on the growth of fruit trees. Under natural conditions, light intensity in the range 1500 to 2100 $\mu mol \cdot sec^{-1} \cdot m^{-2}$ is generally considered adequate for good shoot growth and tree vigor. High light intensity, such as that which occurs in alpine regions, reduces shoot growth (Tukey, 1964; Warrington et al., 1976). Studies with apple or peach have generally shown either no effect (Baraldi et al., 1998; Barden, 1974; Kappel and Flore, 1983) or a reduction in shoot length (Barden, 1977; Jackson and Palmer, 1977; Maggs, 1960) when trees were shaded. But some studies with apple have reported an increase in extension growth when subjected to continuous shade (Auchter et al., 1926; Miller, 2001; Moran, 1991). A combination of blue + far red light, using colored filters, reduced shoot growth (Baraldi et al., 1998; Erez and Kadman-Zahavi, 1972) in peach.

The effect of temperature on shoot growth is more complex than that of light (Rom, 1996), primarily because of its interaction with other environmental factors and its role in regulating the metabolic processes (Flore, 1994; Lakso, 1994). Fruit trees, like all plants, have an optimum temperature range for shoot growth. When temperatures are above or below the optimum range, growth is restricted (Lakso, 1994). A tree growing in a cool cli-

mate will generally have less extension shoot growth than the same tree grown in a warmer climate, all else being equal (Unrath, 1999).

Horticultural practices that reduce shoot growth and tree size

Cultural techniques (such as rootstocks, pruning, scoring, etc.) have long been used to regulate growth and tree size. Pruning, which is universally adopted, is used to rapidly reduce tree size. Management of edaphic resource inputs with irrigation and/or fertilization or resource removal (such as deficit irrigation) with regulated competition are techniques to control tree size. In many instances these techniques are the most expedient, economical, and practical means available to the fruit grower to regulate growth. Most techniques alter the tree's physiology and hormone production resulting in growth suppression or inhibition and possibly changes in tree architecture. Horticulturally imposed growth control techniques and genetic dwarfing are usually additive effects (Faust, 1989).

Site Selection: Although site selection may be beyond the control of the grower, site can have a significant effect on tree growth and site should be chosen with care (Autio et al., 2001; Konishi and Barritt, 1999; Parry, 1977). Site factors that affect growth and tree size are climate and soil. Trees growing on a site subject to spring frost may have greater vigor because of frequent crop losses (Barden, 1999) since resources are focused on shoot growth rather than fruit growth. Sites with a limited shallow or shaley, gravelly soil (A-horizon) with poor water-holding capacity have restricted root growth and thus less top growth (Autio et al., 1990; Rogers, 1946). In the eastern U.S. the effect of site is often quite evident in large orchards where tree rows cross ridges or through areas with significant rock formations that limit soil depth and water holding capacity. On such sites, tree size and extension shoot growth can vary significantly within a row of trees of the same 'stion' (a rootstock-scion combination). Trees grown in the fruit growing districts of Australia and South Africa have shallow and/or heavy clay soils resulting in less shoot growth and smaller trees compared to trees planted in regions with deep, well-drained loam soils.

Rootstocks and interstems: The knowledge that certain rootstocks when grafted to a desirable cultivar produce a tree of reduced size and vigor is centuries old. However, it has only been in the last 50 to 75 years that the commercial fruit industry has taken widespread advantage of this characteristic. While clonal rootstocks provide many benefits not found in seedling roots, one of their primary attributes is the ability to control tree size allowing for high density planting schemes. Faust (1989) concluded that rootstocks control tree size through a direct effect on growth and indirectly through enhanced crop load. The effect of crop load on shoot growth will be discussed later.

The literature on fruit tree rootstocks and their effect on tree performance is extensive and beyond the scope of this review. Readers are referred to the NC-140 (1991, 1996a, b) regional project publications, Autio et al. (2001), Perry et al. (1996), Reighard (1997), Rom and Carlson (1987), Tukey (1964), Webster et al. (2000a), and Zeiger and Tukey (1960) for more background and general information regarding the use and performance of rootstocks for deciduous tree fruits.

Size-controlling rootstocks are more common in apple culture than any other deciduous tree fruit production. Clonal apple rootstocks produce a range of tree sizes from larger than seedling [e.g., 'Malling 25' (M.25)] to 15 to 20% the size of trees on seedling root [e.g.,

M.27 or Polish 22 (P.22)] (Barritt et al., 1997; Ferree and Carlson, 1987; NC-140, 1996b). The relative size relationship for a given apple cultivar over a range of rootstocks is generally consistent from one growing region to another. Thus, 'McIntosh' on M.26 can be expected to produce a smaller tree than 'McIntosh' on M.7A over a wide range of planting sites (Autio et al., 1990; NC-140, 1991). The rootstock effect on tree size is generally discernible in the early life of the tree, but not always (Fallahi and Mohan, 2000). However, the dwarfing effect on shoot extension growth may be less evident, particularly in the first two or three growing seasons (Tukey and Brase, 1941). As the tree ages, the effect of the more dwarfing rootstock can be seen as reduced shoot (Hirst and Ferree, 1996; NC-140, 1996a) or trunk (Fallahi and Mohan, 2000) growth compared to the same cutivar on a more vigorous rootstock. It is suggested that cropping may be associated with the onset of reduced growth (Avery, 1970; Barlow, 1966; Layne et al., 1976).

While a range of size controlling rootstocks is available for pear and stone fruits (peach, cherry, plum, etc.), dwarfing rootstocks for these species have proven less successful commercially than for apple (Rom and Carlson, 1987). Pear trees may range in size from 5 to 130% of a standard tree where size-controlling rootstocks are used. The most common dwarfing rootstocks for pear in the U.S. are the 'Old Home' x 'Farmingdale' and quince (*Cydonia oblonga* L.) selections that result in trees about 50 to 70% of a standard size pear tree (Lombard and Westwood, 1987).

Rootstocks, as a means of growth and size reduction in peach, have been inconsistent and, for the most part, unsuccessful (Reighard, 1997). Inherent scion vigor may be as much or more responsible for the dwarfing effect as the rootstock (Layne et al., 1976). Size control up to 50% has been noted (Layne, 1987) with stocks such as *P. tomentosa* and *P. besseyi* (Rom, 1983). Layne et al. (1976) reported significant reduction in trunk cross sectional area among three peach cultivars in the 6th, 7th, and 8th season with 'Siberian C' rootstock. In contrast, later studies with the 'Redhaven' scion showed little or no difference in trunk size induced by 'Siberian C' compared with more vigorous rootstocks such as 'Halford', Lovell', or 'Bailey' (Layne, 1994). In this study, 'Citation' and 'St. Julien GF 655.2' induced more than a 50% decrease in trunk area compared to the more vigorous stocks.

Clonal rootstocks have recently been developed for cherries that show considerable promise for controlling tree size in commercial orchard plantings (Choi and Andersen, 2001; Perry et al., 1996). Rootstocks derived from interspecific hybrids of *Prunus* in Gembloux, Belgium (the GM series) and Giessen, Germany (the GI series) have produced cherry trees 20% or less than the size of trees on the standard 'Mahaleb' or 'Mazzard' rootstocks (Perry et al., 1996). The most promising dwarfing cherry rootstocks produce trees between 20 and 50% of a standard size tree.

Rootstocks can impose a dwarfing effect by grafting the stock and scion together, but other methods are also effective. One approach is to graft a piece of bark (phloem) tissue from a dwarfing stock onto the scion (Lockard and Schneider, 1981). Grafting a piece of dwarfing stock (an interstem or interstock) between the scion cultivar and a more vigorous rootstock will also reduce scion vigor in several fruit tree species (Ferree, 1992a; Perry, 1987; Reighard, 1998) and has been used commercially in apple (Ferree and Carlson, 1987) to produce "interstem" trees (e.g., an MM.111/

M.9 tree). The length of the interstem influences the degree of vigor control; the longer the stem piece the more the scion is dwarfed. An apple tree using an M.9 interstem will be slightly larger than the same tree growing directly on an M.9 rootstock (Ferree and Bishop, 1988). In addition, if the full length of the interstem is exposed above the ground when planted, the resulting tree will be slightly smaller than if the union between the interstem and the rootstock is buried below ground level. Bridge grafting several apple cultivars on vigorous rootstocks (MM.106, M793, or 'Northern Spy') using M.9 shoots has also been shown to reduce shoot growth up to 20% (Samad et al., 1999). The height of budding can also affect scion vigor with higher budding on the rootstock resulting in more dwarfing (Perry, 1987; Van Oosten, 1978).

***Pruning and root restriction*:** It is well established that, when a portion of the fruit tree is removed by pruning, the resulting tree is smaller. Pruning is a dwarfing process, but growth is stimulated in the vicinity of the pruning cut (Forshey et al., 1992; Geisler and Ferree, 1984; Mika, 1986; Myers, 1990; Talbert, 1940; Westwood, 1978). Pruning can be used as dormant, summer, or root pruning.

Dormant pruning: Dormant pruning reduces trunk size (Alderman and Auchter, 1916; Elfving, 1990; Maggs, 1965) and canopy volume (Alderman and Auchter, 1916; Talbert, 1940; Mika et al., 1983) compared to the same tree that is not pruned. Generally speaking, the more severe the pruning the greater is the dwarfing effect on trunk, branch and/or canopy size (Barden et al., 1989; Miller and Byers, 2000; Savage and Cowart, 1942). Miller and Byers (2000) reported a 21% reduction in canopy volume when peach trees were severely pruned compared to unpruned trees or lightly pruned trees. The effect on canopy volume from a single severe dormant pruning lasted through the four years of their study. Elfving (1990) also found a single severe pruning to affect tree size and yield for more than one season in apple. Dormant hedging or shearing, which is a non-selective heading-back type pruning, has shown some success in controlling tree size, but this practice often results in a proliferation of shoots over the periphery of the tree resulting in a very dense canopy (Ferree and Lakso, 1979; Forshey et al., 1992).

The response to dormant pruning cannot be simply characterized in terms of reduced tree size, however, since the total response depends on a number of factors (Mika, 1986) including the type of pruning cut used. When a heading cut is used to remove a shoot, the 2 or 3 buds immediately below the pruning cut are invigorated. The growth of the new shoots that are produced will generally be greater than the growth of shoots on a similar nonpruned branch (Elfving and Forshey, 1976), but there are exceptions (Lord and Damon, 1983). Mean shoot length also increases with the severity of pruning (Barden et al., 1989; Elfving and Forshey, 1976; Jonkers, 1982). Thus, to the casual observer the effect of dormant pruning may seem to be stimulated growth, but the total dry matter produced by the pruned tree is less than the nonpruned tree (Myers and Saville, 1996). To avoid this localized, invigorating effect it is recommended that pruning consist primarily of thinning cuts and that few heading cuts be used (Forshey et al., 1992; Marini et al., 1993; Myers, 1990). Thinning cuts that remove an entire shoot or branch back to the point of origin accomplish much of the same dwarfing effect without stimulating adjacent buds into vigorous growth.

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dwarfing than dormant pruning; however, recent reviews (Marini and Barden, 1987; Saure, 1987) indicate that much of the evidence to support this claim is inconclusive. Many factors influence the growth response to summer pruning (Forshey et al., 1992; Mika, 1986; Saure, 1987; Stembridge, 1979) principally the type of cut used, the timing, and severity (Miller, 1982; Walsh et al., 1989). Studies with apple (Alderman and Auchter, 1916; Ferree and Rhodus, 1993; Maggs 1965; Myers and Ferree, 1983; Taylor and Ferree, 1984), peach (Leuty and Pree, 1980), cherry (Flore, 1992; Kappel et al., 1997; Mika and Piatkowski, 1989), and plum (Mika and Piatkowski, 1989) report that summer pruned trees are smaller than dormant pruned trees. Marini (1985) reported that the effect on tree size in peach varied with cultivar. Miller (1982) found that regrowth following summer pruning of vigorous 'Topred Delicious' apple trees depended on time of pruning after full bloom (FB) and whether heading cuts were made in current season wood or 1-year-old wood. When pruning was delayed until 16-weeks after FB, regrowth was significantly reduced compared to 8-weeks after FB. Several studies have reported reduced shoot growth following summer pruning (Elfving and Cline, 1990; Mika, et al., 1983; Rom and Ferree, 1984; Taylor and Ferree, 1984), while others have reported no effect (Ferree and Rhodus, 1993; Goldschmidt-Reischel, 1997) or increased shoot growth (Greene and Lord, 1983; Taylor and Ferree, 1984). Marini and Barden (1982) summer pruned one- and two-year old 'Delicious' apple trees and found trunk growth, shoot growth, and root growth were reduced. However, in the year following treatment, growth of summer-pruned trees was similar to comparably dormant-pruned trees. Later, Barden et al. (1989) reported the growth response to summer pruning in August was very similar to dormant pruning in February. Elfving and Cline (1990) reported summer pruning reduced shoot length on vigorous 'Northern Spy' apples in 4 of 5 years applied and reduced dormant pruning time in all five years, but summer pruning did not replace the need for dormant pruning. Because there were no benefits on yield, they concluded that summer pruning was ineffective for controlling vegetative growth. The general conclusion drawn by those who have reviewed summer pruning (Gardner et al., 1952; Marini and Barden, 1987; Saure, 1987) is that summer pruning is no more dwarfing or devitalizing than dormant pruning. Recent studies (Elfving and Cline, 1990; Goldschmidt-Reischel, 1997; Guimond et al., 1998; Kappel and Bouthillier, 1995; Kikuchi et al., 1989) provide no compelling evidence to alter this conclusion.

Root pruning and root restriction: Limiting the uptake of resources has been achieved by manipulating root systems of fruit trees. Two approaches include pruning and restricting soil volume of root systems. These techniques can significantly disrupt a peach tree root system in which 50 to 60% of the roots are in the top 30 cm of soil and 90% are in the upper 60 cm of soil (Havis, 1938). In apple, 79% of all roots have been found in the upper 30 cm of soil (Susa, 1938). Physical reduction of root growth should decrease resource uptake or create a plant growth substance (PGS) (plant hormone) imbalance which can adversely affect shoot growth. A simple allometric change could reduce shoot growth until a more favorable root-to-shoot ratio is established and shoot growth is no longer inhibited. Pruning and restriction of fruit tree root systems has been successful with some researchers but less efficacious with others.

Pruning roots of young and mature apple trees reduced shoot growth and thus controlled tree size (Ferree, 1989, Schupp and Ferree, 1988). Root pruning at 80 cm from the trunk each

year for nine years, reduced the number of apple tree roots, particularly in the top 30 cm of soil (Ferree, 1994b). In 15-year-old apple trees, this method of root pruning reduced trunk cross-sectional area (TCSA) and shoot length without reducing fruit yield (Schupp and Ferree, 1988). A later study indicated that yield, as well as TCSA, was reduced by root pruning in 'Golden Delicious' apple trees that were grown on different rootstocks and interstems (Ferree and Knee, 1997). Root pruning reduced shoot growth and fruit load in 'Empire' and 'McIntosh' apple trees (Elfving et al., 1996). Timing was important and root pruning in the dormant season or at full bloom was more effective in reducing shoot elongation than at June drop (Schupp and Ferree, 1987). Similar results were obtained with peach where root pruning in April was more effective for reducing shoot elongation than root pruning in June (Santos et al., 1991).

In apple trees, root pruning was more effective in reducing shoot growth when trees were cropping (Schupp et al., 1992). Fruit presence was critical as it appeared to reduce carbon allocation to roots and extended the time in which the root-shoot balance was upset. However, root pruning has not proven consistent for shoot growth control (Miller, 1995) when most needed under low cropping, high vigor trees. It may well be that the size and depth of fruit tree root systems are so widely distributed and soil resources are heterogeneously dispersed that removing a portion of a root system cannot provide predictable, reliable effects on shoot growth. Reduced fruit size and yield associated with root pruning may limit its use as a remedy where shoot growth requires extreme corrective control (Ferree and Knee, 1997).

Despite the growth inhibition effects, root pruning may not be economical to manage tree size for high density plantings as an alternative to simply planting apple trees at an appropriate spacing (Ferree and Rhodus, 1993). One problem is that abundant rainfall can negate the potentially inhibitory effects of root pruning (Ferree, 1992b). Root pruning had no effect on vegetative growth of peach trees, as measured by pruning weights (Glenn and Miller, 1995).

Interactive effects of root pruning and other procedures to inhibit growth have been studied. Miller (1995) found that effects of root pruning and trunk scoring were inconsistent on fertile soils that received trickle irrigation. Neither technique was recommended to manage growth of apple trees. Baugher et al. (1995) found that the combination of root pruning and grass competition reduced growth of apple trees, but results were inconsistent between years.

Physical restriction of roots has been used to regulate shoot growth of fruit trees. Williamson and Coston (1990) dwarfed peach trees by planting them at high density in fabric-lined trenches. The root restriction increased yield efficiency, but size of individual peaches was smaller. The physical barrier of a fabric-lined trench was later shown to reduce peach shoot growth more than grass competition with narrow herbicide-treated strips (Williamson et al., 1992). Root restriction may have caused a nutrient deficiency or disrupted PGS production in young peach tree cuttings, which reduced stem elongation (Rieger and Marra, 1994). Myers (1992) reduced canopy growth of peach and apple trees by restricting root volume in three-year-old trees. Restricting root volume of young peach trees reduced production of secondary lateral branches without inducing water stress (Boland et al., 1994). Ran et al. (1994) suggested that physical restriction of roots in peach trees may reduce N uptake and the

subsequent synthesis of root-produced PGSs. These experiments were conducted with young trees that were root restricted from the time of planting. Little (or no) information is available regarding long-term effects of root restriction on fruit tree growth and yield, however, some observations suggest these techniques impose a substantial barrier to any roots beyond the fabric.

Indirect root restriction (i.e. without physical barriers) has been obtained by irrigation or fertigation to parts of a fruit tree root system (Bravdo et al., 1992). In this experiment, roots proliferated in the wet but not the dry soil so that portions of the root system were "restricted" to a limited volume similar to limiting roots with a physical barrier. Shoot growth of peach trees can be managed by regulating the mineral and water availability to roots but the precision necessary for this approach can be problematic and restricting root systems with a physical barrier was proposed as a viable alternative (Richards and Rowe, 1977a, b). Leaf stomatal conductance and leaf water potentials could not explain reduced shoot growth in root-restricted apple trees (Webster et al., 2000b). It was suggested by these authors (Richards and Rowe, 1977a, b; Webster et al., 2000b) that limitation of root systems could interfere with production of PGSs and thus influence shoot growth. An alternative is partial root restriction using fabric barriers with larger hole sizes that limits root penetration to small roots and girdling larger roots (Ross Byers, personal communication).

The variability in fruit tree response to root pruning and root restriction is likely due to the imprecision of these techniques and to heterogeneity of environment. Pruning depth and distance from the tree trunk and the length of the pruning cut will influence the amount of root cut and, consequently, the impact on vegetative shoot growth. Edaphic heterogeneity, such as patchy nutrient distribution or uneven water availability will also affect the distribution of roots prior to pruning and the response of the tree following pruning. One may conclude that root pruning and root restriction can be used to modify fruit tree vegetative growth but simple generalizations do not seem possible at this time.

Branch orientation: Apical dominance, gravity, and plant hormones play major roles in the growth response of shoots. Vertically oriented branches on fruit trees are usually more vigorous (Elfving and Forshey, 1976; Myers and Ferree, 1983) and less productive than branches oriented in a more horizontal position (Tromp, 1970). Bending or spreading branches to a more horizontal position is an old practice (Tukey, 1964) that has several benefits including reduced terminal growth, enhanced lateral growth and spur formation, and increased flowering and fruiting (Forshey et al., 1992). While branch bending was long practiced by European fruit growers, its commercial use in North America was limited, and even discouraged (Gardner, 1917), until the early 1970s when methods were proposed and promoted for training central leader (Heinicke, 1975) and related tree forms for high-density planting systems (Forshey et al., 1992).

Wareing and Nasr (1961) provided one of the first detailed investigations on branch orientation using apple, cherry, and plum. Their studies clearly demonstrated the effect on the growth of the apical and lateral buds along the shoot when vertical shoots are re-orienting to the horizontal. In these studies, terminal shoot growth was reduced significantly and growth of lateral buds was increased. Buds on the upper side of horizontal shoots generally produced vigorous shoots while buds on the lower side remained dormant or produced short spurs. The authors suggested the ef-

fects resulted from the gravitational distribution of growth hormones. Later studies by Mullins (1965) and Mullins and Rogers (1971) provided additional evidence and support to the theory proposed by Wareing and Nasr (1961) while studies by Kato and Ito (1962) provided evidence for the role of auxins and gibberellins. Ethylene, generated as a stress response to bending, is also involved in the growth response to limb bending (Rom, 1989). Earlier studies on branch orientation generally compared only vertical and horizontal shoots. When lateral branches on young field-grown, central leader apple trees were bent to a horizontal position, shoot growth was reduced, but growth of the leader was increased and total growth was not different from control trees where laterals were permitted to grow at a natural angle (Mika, 1969); in this study, fruit buds were not increased by bending. Elfving and Forshey (1976) reported that bending shoots on vigorous 'Delicious' apple trees to a horizontal position reduced shoot growth by about 80% compared to vertical shoots. When the horizontal shoots were headed by removing 2/3 of the previous season's growth, shoot length was significantly less than both pruned and non-pruned vertical shoots. Total shoot growth for horizontal shoots was significantly less than upright shoots regardless of pruning treatment. Elfving and Forshey (1976) did not report the effect of bending on flowering or fruiting.

Hamzakheyl et al. (1976) oriented shoots on newly planted 'Oregon Spur Delicious' trees at 30°, 60°, or 90° and found that shoot growth was reduced proportional to the degree of bending toward the horizontal. Total growth of control trees (not spread or pruned and average branch angle of 42°) was 40% more in the first season and 300% more in the second season compared to all spreading treatments. Trees with shoots trained to 90° had the fewest number of spurs and the greatest number of vigorous watersprouts. Production of vigorous shoots near the base of limbs bent near or to 90° from vertical was observed by Wareing and Nasr (1961) and has been reported by others (Dann et al., 1990; Kaini et al., 1984). Shoots trained at an angle of 30° the first season and 60° the second season had the greatest reduction in shoot growth in the second season and the highest number of flower clusters among all treatments. Myers and Ferree (1983) tagged limbs growing between vertical and horizontal on vigorous 5-year-old 'Red Prince Delicious' trees. They found total length and number of shoots was greater on vertical than horizontal limbs. Myers and Ferree (1983) also found that summer pruned (July) vertical limbs produced more regrowth than horizontal limbs, which is similar to the findings of Elfving and Forshey (1976) with dormant pruning. In the study by Myers and Ferree (1983), vertical limbs had more flowers than horizontal limbs, but fruit set did not differ based on limb orientation. Greene and Lord (1978) spread limbs on vigorous non-spur 'Delicious' trees in two years resulting in reduced terminal shoot growth and increased blossom clusters, but fruit numbers were not affected. They did not indicate the angle to which limbs were spread. Ferree (1994) reported that limb bending on young 'Smoothee Golden Delicious' and 'Lawspur Rome Beauty' apple trees reduced shoot growth slightly in the second season of bending but had no significant effect on tree size (height, spread, and canopy volume) or yield over four seasons.

Like many cultural practices, the response to branch spreading depends on a number of factors including cultivar and growth habit, timing, tree age, rootstock, and degree of spreading (Myers and Savelle, 1996; Rom, 1989). Suggested training methods for many of the current high-density apple systems is to reposition strong upright shoots below the

leader to near horizontal or even below the horizontal to reduce vigor and encourage fruiting (Barritt, 1992; Forshey et al., 1992; Oberhofer, 1990). Systems such as the Hybrid Tree Cone suggest bending the leader of vigorous cultivars at a 45° angle to the vertical each year, in addition to spreading lateral branches to 30° or less above horizontal, to slow growth and encourage flowering (Barritt, 1992). Spur-type apple cultivars with a basitonic (e.g., 'Starkrimson Delicious') growth habit produce the best balance between growth and fruiting if limbs are spread to 45° while natural spreading cultivars (e.g., 'Golden Delicious') respond best to spreading 60° or more from vertical (Forshey et al., 1992). Stebbins (1980) recommends spreading 'Comice' and 'Bosc' pear, but not 'Bartlett' and 'Anjou'. Spreading is now recommended for high-density sweet cherry systems to reduce growth (Long, 1999). Spreading or bending in peach has focused on inclined canopy systems (Dann et al., 1990; DeJong et al., 1992) rather than spreading of individual branches to achieve growth control.

A radical form of branch orientation is looping (Byers and Carbaugh, 1987). Shoots or the trunk of a young tree are bent to form a loose loop or knot to restrict growth. McLean (1940) inhibited terminal growth in 2-year-old sweet cherry by looping the trunk. Byers and Carbaugh (1987) used various sized loops on 'Starking Fullred Delicious' apple trees grafted to seedling roots and found reduced terminal shoot length in each of five years of the study compared to unlooped trees. A large loop (17.0 cm diameter) suppressed terminal growth more than a small loop (8.5 cm diameter) in the second and third year of the study. When they compared one large loop (15 cm) with one or two small loops (7.5 cm) on five apple cultivars, all looping treatments reduced terminal shoot growth measured annually over four years. Dwarfing was most enhanced by two 7.5-cm loops > one 15-cm loop > one 7.5-cm loop > no loop for most cultivars. Terminal shoot growth of sweet cherry was not affected by one 7.5-cm loop.

***Scoring, girdling, and bark inversion*:** Scoring is an ancient technique used primarily to enhance fruiting, that can also reduce shoot growth (Greene and Lord, 1986; Tukey, 1964). A single knife cut through the bark reaching to the xylem tissue (wood) that encircles the trunk or stem is the process of scoring a tree. A severe form of scoring is called girdling or ringing. With girdling, a piece or "ring" of bark, usually about 2 to 6 mm wide, is removed around the trunk or stem. Most studies on scoring or girdling have focused on apple, since apple is generally responsive and healing of the wound is more rapid than in other tree fruits, thus avoiding disease problems. Scoring was correlated with winter injury on 'Gravenstein' apple in Nova Scotia when cuts healed poorly (Embree and Crowe, 1985) and caution is urged in girdling peach or plum when used to increase fruit size (Day and DeJong, 1999) because of potential disease and winter injury problems. Several tools are available to make girdling cuts of a specified and uniform size; chainsaws have also been employed to girdle large apple trees (Hoying and Robinson, 1992). Scoring and girdling, much like branch orientation or cropping, affect assimilate partitioning and the flow of nutrients and growth hormones that leads to growth and fruiting responses (Cutting and Lyne, 1993; Forshey and Elfving, 1989; Kato and Ito, 1962). Scoring or girdling may produce responses in the year following treatment, but Hennerty and Forshey (1971) indicate the effects are not related to carbohydrate reserves (assimilate partitioning).

A number of studies have reported reduced shoot (Batjer and Westwood, 1963; Cutting and Lyne, 1993; Greene and Lord, 1978, 1983;

Miller, 1995; Veinbrants, 1972; Wilton, 1999) and/or trunk (Autio and Greene, 1994; Batjer and Westwood, 1963; Greene and Lord, 1983; Miller, 1995) growth when fruit trees are scored or girdled. The technique is generally considered most effective for controlling shoot growth in the year the procedure is performed (Batjer and Westwood, 1963; Greene and Lord, 1978), but it may also affect growth for one or more years after the treatment (Greene and Lord, 1978, 1983; Hoying and Robinson, 1992). Veinbrants (1972) reduced final shoot length by 25% when he scored 'Granny Smith' apple trees soon after bloom. If scoring was delayed by 2 weeks, shoot growth was reduced by only 12% compared to control trees. Wilton (1999) recently demonstrated a progressive loss in shoot growth control on 'Pacific Rose' apple trees as scoring timing progressed from petal fall (PF) to 6.5 weeks after PF.

Greene and Lord (1978) trunk scored a different group of young 'Richared Delicious' apple trees about 2 weeks after FB in each of the three years from 1973 to 1975 and reduced terminal shoot growth by 51, 26, and 31% respectively. Trees scored in 1975 had about 35% less shoot growth in 1976 compared to controls. In a later study, Greene and Lord (1983) scored 5-year-old 'Cortland' apple trees 19 days after FB one year and reduced TCSA increase for the next 3 years and terminal growth for two years. Girdling mature 'Macspur McIntosh' trees with a chain saw reduced average shoot length by 18% and shoot numbers by 20%. When reestablishing the girdles for 2 more years, growth control was similar to that achieved with a single season's girdle (Hoying and Robinson, 1992). Ringing or scoring vigorous 15-year-old 'Gardiner Delicious' and 16-year-old 'Rogers Red McIntosh' apple trees resulted in significantly smaller increases in TCSA compared to control trees, but shoot length was not affected. Miller (1995) found no effect on terminal shoot growth when he scored 3-year-old 'Gala', 'Empire', and 'Jonagold' apple trees on M.7A rootstock planted at a 1.8 m in-row spacing. Miller (1995) suggested that trees growing on deep fertile soils supplied with irrigation may be too vigorous to respond to scoring. Veinbrants (1972) also reported no effect when he scored 8-year-old 'Gravenstein' apple trees growing under clean cultivation and with irrigation. Because flowering was increased, Veinbrants (1972) suggested that extension growth and flower initiation were independent.

Stang et al. (1976) reduced shoot growth 14 to 25% when they scored young 'Red Prince' or 'Melrose' apple trees; shoot growth control from scoring was similar to that obtained with sprays of the plant growth regulator daminozide. In New Zealand, Wilton (1999) noted that the effect of scoring or girdling was quite similar to the response obtained from root restriction techniques.

A procedure similar to girdling, but less severe is bark inversion (Sax, 1957; Tukey, 1964). A ring of bark is removed as in girdling and replaced in an inverted position. The inverted polarity of the phloem temporarily slows vegetative growth and promotes flowering (Sax, 1957). Sax (1957) indicated the procedure should be done during the normal period for fruit bud differentiation and the effect on young trees may last for several years.

Fertilization: Adequate soil fertility is crucial for successful cropping but over abundant nutrients can cause excessive and undesirable vegetative shoot growth. It can be difficult to fertilize so that only shoot growth is controlled without adversely affecting root growth or yield. Fertilization can disproportionately increase root and shoot growth so that the root-to-shoot ratio decreased in apple

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trees (Robinson et al., 1992). Tree growth control with selective application of fertilizer is further made difficult by the potential reservoir of minerals stored in the perenniating portions of the tree. Niederholzer et al. (2001) found that peach tree growth in spring drew strongly from stored N, independent of N supplied in the fall. Root uptake of N by apple trees was negligible in early spring because trees used more of the stored N (Neilsen and Neilsen, 2002). Greater N use efficiency resulted when N was applied to the soil after reserve N was remobilized from storage tissue in apple in early spring.

Fertilizers are often targeted for application below a fruit tree canopy dripline. In young apple trees grown in herbicide-treated strips with grass alleys between the strips, most root growth and nutrient uptake occurs in the herbicide strip (Atkinson, 1977). Effects of fertilizer on growth of young trees is linked to fertility in the herbicide strips. However, as trees age, their root systems extend into grass alleys, particularly at depths below the grass roots. Therefore, the distribution of a mature apple root system may not necessarily be related to the zones of active ion uptake (Atkinson, 1974). Withholding fertilizer to maintain a desired tree size is obviously difficult because of spatial and temporal variation in nutrient availability and uptake in young and mature trees but carefully managed fertilization should help reduce undesirable vegetative growth.

Deficit irrigation: Like soil fertility, soil moisture can be modified to regulate fruit tree growth. Soil water has been managed to regulate tree growth, particularly in peach. This approach is successful when soil water is limiting and irrigation can stimulate growth and yield. Irrigation at selected times during the growing season has been shown to reduce vegetative growth without adversely affecting yield in peach and pear (Chalmers et al., 1981; Mitchell et al., 1989). This form of irrigation, which is restrictive to shoot growth, is termed deficit irrigation.

Dormant pruning of peach can be reduced by one-third if post-harvest irrigation is withheld in areas of California with little or no summer rainfall (Larson et al., 1988). Withholding irrigation during the dry summer thus can help reduce vegetative growth of peach (Ghrab et al., 1998; Johnson et al., 1992). Deficit irrigation may lead to tree adaptation to dry conditions. When reduced irrigation was extended over 4 years, peach trees extracted more of their water from deeper soil (Johnson et al., 1992).

Apple trees also respond to deficit irrigation but responses are not identical to peach. In regions with abundant rainfall, such as the eastern U.S., reducing soil water with under-canopy covers did not affect terminal shoot growth in apple (Erf and Proctor, 1989). However, covers in defruited trees reduced trunk growth. Growth response of apple to soil water availability will vary with rootstock. By regulating irrigation, Fernandez et al. (1997) demonstrated that apple trees on dwarfing rootstock (M.9 EMLA) were reduced less by drought than the apple trees on more vigorous rootstock (MARK). These results suggest that cultural management of fruit tree size, e.g. by deficit irrigation, will also be affected by the rootstock/scion being used.

Combinations of deficit irrigation and managed competition or reduced tree root volume have been used to control tree growth. Shoot growth of peach trees was reduced when annual ryegrass (*Lolium multiflorum* Lam.) was seeded beneath peach trees to deplete excess moisture and ryegrass was later killed as fruit enlarged (Huslig et al., 1993). In that study, pan evaporation had been used to

schedule irrigation by replacing 60% of evaporation. Rooting volumes can interact with available soil water to affect vegetative growth of peach trees. Reduced root volume had little effect on shoot growth when deficit irrigation was applied with 30% replacement of water that had been used (Proebsting et al., 1989). However, in full-irrigated soil, shoot growth was proportional to soil volume. In that study, water was fully available and only root volume restricted growth under the latter condition.

Regulated deficit irrigation may be most effective to control shoot growth when used in conditions, such as dry regions of Australia, where stress can be applied early and quickly, particularly in shallow soils (Johnson and Handley, 2000).

Competition: Controlled fertilization and irrigation provide fruit tree growth regulation by managing resource inputs but nutrients and water can also be removed from fruit trees with managed competition. This competition can be intraspecific and vary with tree density or interspecific and vary with density and competitiveness of selected ground covers. Researchers have long known that changing the size of vegetation-free strips in which fruit trees were planted provided a means of managing competition and thereby regulate fruit tree growth (Glenn et. al., 1996; Merwin and Stiles, 1994; Shribbs and Skroch, 1986; Yocum 1937). The efficacy of managed competition appears to be dependent on edaphic conditions and on tree size when managed competition is implemented.

Permanent grass strips or driveways between tree rows can remove water and reduce vegetative growth of peach trees during the first five years after planting at high density (633 trees / ha) (Layne and Tan, 1988). This growth inhibition was overcome with trickle irrigation, suggesting that combinations of ground cover competition and irrigation can manage tree growth. Similar results were obtained with trees four through nine years after planting (Glenn et al., 1996). The vegetative growth of peach trees was related to the size of the herbicide-treated row, i.e. the amount of competition (Glenn et al., 1996).

In addition to soil moisture, ground covers were shown to reduce N and probably other nutrients such as B. In the field, peach tree root density decreased when tree roots encountered grass roots (Glenn and Welker, 1989; Parker et al., 1993). Roots of young peach trees did not grow in the soil where grass roots were dense which reduced root system size and, consequently, reduced shoot size since peach appeared to maintain an allometric equilibrium between root and shoot (Tworkoski, 2000). Often leaf nutrients, such as N, of fruit trees are reduced when trees are grown with grass competition and this reduction is usually assumed to be due to the superior ability of the grass to remove nutrients (Tworkoski et al., 1997). Managed competition thus reduces tree root growth and nutrient uptake of trees that, separately or together, can reduce shoot growth.

Apple tree growth has also been reduced by weed competition (Schupp and McCue, 1996). The timing of competition may also be important. Merwin and Ray (1997) determined early-season weed competition was particularly important when interfering with growth of newly planted apple trees. Together, these experiments indicate that young fruit tree growth can be reduced by competition but managed inputs, such as irrigation are probably necessary to prevent loss of yield. On a practical level, the economic gains of grass competition (smaller trees easier to manage and harvest) must be weighed against the cost

(need for irrigation, higher initial capital outlay for more trees to fill space in the orchard) but managed competition can be used to dwarf fruit trees.

In mature trees, grass competition can reduce peach tree root growth and growth of fruit-bearing shoots as well as water sprouts (Tworkoski and Glenn, 2001). However, the reduction in shoot growth did not translate to economic savings such as reduced time for winter pruning. The conclusion was that installing grass beneath mature peach trees was not beneficial for managing peach tree vegetative growth following pruning but there may be other benefits for soil improvement and control of broadleaved weeds.

Tree size has been modified with planting density and intraspecific competition. Weights of 4-year-old apple tree shoots and roots decreased as planting density increased and the root/shoot weight ratio remained constant (Atkinson et al., 1976). The combination of higher tree density and regulation of soil resources has also been successful. Intraspecific competition among peach trees did not reduce vegetative growth but growth stimulation with irrigation was reduced by competition in high-density plantings (Chalmers et al., 1981). In similar studies with pear planted at three in-row spacings, TCSA was reduced at the closest spacing and lowest irrigation level, but as irrigation levels increased, the effect was reversed (Mitchell et al., 1989). These studies demonstrate that orchard floor competition with fruit trees can limit mineral and water availability but that competition can also limit root growth, leading to an allometric reduction in shoot growth and tree size. In contrast, Clayton-Greene (1993) found a highly significant effect of planting density on TCSA in 'Granny Smith' and 'Starking Delicious' apple when grown at densities ranging from 687 to 3175 trees per hectare among several training systems; as density increased TCSA decreased. Trees in this study received a fully recommended level of irrigation. Similar reductions in TCSA and/ or shoot growth have been reported in other areas on apple (Mika and Piskor, 1997), peach (Marini and Sowers, 2000), and nectarine (Loreti et al., 1993) as planting density increases.

Cropping: Horticulturists have long recognized the interrelationship between vegetative and reproductive development in fruit trees. Cultural practices that affect growth will generally affect fruiting and vice versa. Bukovac (1981) presented a discussion on the subject and Forshey and Elfving (1989) provided an in-depth review on the close relationship between vegetative growth and fruiting in apple trees.

Numerous studies have shown that fruiting reduces growth (shoot, trunk, and/or root growth or dry weight of tree parts) (Avery, 1970; Barlow, 1966; Forshey, 1982, 1989; Glenn and Welker, 1993; Grossman and DeJong, 1998; Kato and Ito, 1962; Maggs, 1963; Proebsting, 1958; Taylor and Ferree, 1984; Volz et al., 1993; Weinbaum et al., 1994). Fruiting in 'Golden Delicious' apple trees reduced shoot growth by about 34%, reduced TCSA increase about 54%, and reduced specific leaf weight 8% compared to trees defruited shortly after bloom (Erf and Proctor, 1987). Volz et al. (1993) compared heavy and lightly cropped 10-year-old 'Cox Orange Pippin' apple trees and found TCSA increased by 62% more in the lightly cropped trees. Similar effects on TCSA were reported when pruned trees were defruited (Weinbaum et al., 1994). However, not all studies have shown a reduction in vegetative growth associated with increased fruiting (Curry and Looney, 1986; Taylor and Ferree, 1984). 'Goldspur Golden Delicious' apple trees in the "on" year consistently had more extension

shoot growth than trees in the "off" year (Curry and Looney, 1986). Several other studies demonstrate that the effect of fruiting on growth is not manifested in the "on" year, but rather in the following "off" year (Forshey, 1982; Rogers and Booth, 1964). Forshey and Marmo (1985) reported that increased shoot growth following deblossoming was due to an increase in shoot numbers and not to longer shoots, a finding that supported earlier work by Forshey (1982). Barlow (1966) had suggested that fruiting reduced the number of growing points that develop into long shoots. While shoot growth can be reduced significantly by fruiting, root growth is probably more sensitive to cropping (Maggs, 1963) and may be almost totally stopped by the effect of cropping (Avery, 1970; Jackson, 1984; Palmer, 1992).

Cropping has been associated with reduced total tree leaf area and leaf dry weight compared to non-cropped trees (Hansen, 1971). Forshey and Elfving (1989) reported that total shoot leaf area is closely related to total shoot growth and the percent shoot leaves is positively related to shoot growth and negatively related to yield. Cropping reduced leaf growth and stem growth on various peach training systems (Grossman and DeJong, 1998) in California. Studies in New Zealand on young 'Braeburn'/M.26 apple trees with crop loads ranging from 0 to 57 kg per tree showed a significant decreasing linear trend in leaf area from no crop to high-cropped trees (Wünsche et al., 2000); low cropped trees had higher shoot numbers and greater shoot length than high cropped trees. In contrast Palmer (1992) found no significant reduction in leaf area with increasing fruit load over 2 seasons in 'Crispin'/M.27 apple trees. The cropping – shoot growth relationship is a complex interaction likely associated with assimilate partitioning and the source-sink strength of various plant parts within cropping and non-cropping trees (Forshey and Elfving, 1989). Recent studies have provided additional information toward an explanation of this interaction (Palmer et al., 1997; Schechter et al., 1994; Wünsche et al., 2000).

Plant growth regulators: The development and use of exogenous plant growth regulators (PGRs) as growth retardants can be attributed to the knowledge that endogenous plant hormones play a significant role in shoot growth. Growth retardants, as defined by Davis and Curry (1991), are compounds "which reduce plant size without obvious phytotoxicity." While growth regulators other than retardants (such as herbicides) at low concentrations may reduce shoot growth without phytotoxicity (Davis and Curry, 1991), adverse effects on productivity are common (Rademacher, 2000) and for this reason their practical use is limited.

All the major PGSs are likely involved in shoot growth, but among them gibberellins (GAs) have received the most attention because of their key role in cell elongation (Faust, 1989; Luckwill, 1970; Rademacher, 2000). Since the early 1960s synthetic GA biosynthesis inhibitors have been extensively researched as practical tools to control vegetative growth in tree fruits. In addition, ethylene releasing compounds, and synthetic auxins have also been studied and proven effective in controlling shoot growth (Miller, 1988). The subject of PGRs as vegetative growth retardants in various fruit crops has been reviewed (Davis and Curry, 1991; Looney, 1983; Miller, 1988; Williams, 1984).

Daminozide [butanedioic acid mono (2,2-dimethylhyrazide)], a GA biosynthesis inhibitor (Rademacher, 2000), was the first synthetic PGR to exhibit strong vegetative growth retarding properties in fruit trees (Batjer et al., 1963). The ability of daminozide to reduce growth in apple and pear at rates between 1000 and 10,000 $mg \cdot L^{-1}$ is well docu-

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mented (Miller, 1988). Daminozide is also effective in reducing shoot growth in cherry (Proebsting and Mills, 1976; Unrath et al., 1969), but has shown only minimal effect on peach shoot growth (Byers and Emerson, 1969). The use of daminozide on tree fruit crops was discontinued in 1989 due to suspected toxicological risks and cancellation of the label registration by the U.S. Environmental Protection Agency. Chlormequat (2-chloro-N,N,N-trimethylethanaminium chloride) is another of the earlier GA biosynthesis inhibitors to exhibit growth retarding effects in fruit trees (Davis and Curry, 1991). Chlormequat has limited activity in apple (Miller, 1988) but is an effective shoot growth retardant in pear where its activity is similar to daminozide (Embree et al., 1987). Chlormequat was not registered for use on fruit trees in the United States, but is labeled for use in many European countries for pear. Edgerton and Blanpied (1968) first recognized the growth controlling properties of ethephon (2-chloroethylphosphonic acid) on apple.

Ethephon at 2000 $mg \cdot L^{-1}$ applied to actively growing apple shoots was as effective as equal rates of daminozide in reducing shoot growth. A combined spray of ethephon and daminozide was more effective for growth suppression than either material applied alone (Byers and Barden, 1976). However, because early postbloom sprays, which affect maximum growth control, reduce fruit set, ethephon has not received widespread use as a growth retardant (Davis and Curry, 1991; Miller, 1988). Byers (1993) demonstrated that multiple low-dose (100 to 200 $mg \cdot L^{-1}$) sprays applied at weekly intervals during the first 45 days after FB reduced shoot growth without excessive fruit abscission in 'Starkrimson Delicious' apple trees. Byers (1993) reported that flowering and fruit set were increased in the year after application and the subsequent cropping contributed to reduced growth. Single low-dose (50 to 250 $mg \cdot L^{-1}$) applications have not proven effective in controlling shoot growth in 'Empire' apple trees (Elfving and Cline, 1993).

Vigorous shoots produced from latent buds on the trunk (watersprouts) or from adventitious buds below the soil line (rootsuckers) on apple and pear can be suppressed effectively with various formulations of 1-naphthaleneacetic acid (NAA). This subject has been thoroughly reviewed by Miller (1988) and no additional review is warranted at this time.

Success with daminozide, ethephon, and chlormequat sparked interest in the search for new PGRs with growth controlling activity. In the late 1970s and early 1980s research was begun on several triazole compounds, the most promising of which was paclobutrazol {â-{(4-chlorophenyl)methyl]-á-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol} (Williams and Edgerton, 1983). The primary mode of action for the triazoles is via GA biosynthesis inhibition (Rademacher, 2000), however, evidence exists that other activities with specific enzymes or plant hormones may be involved (Davis and Curry, 1991). Paclobutrazol and the related triazoles have several unique properties that distinguish them from other GA biosynthesis inhibiting growth retardants (Miller, 1988) most notably a strong residual effect, a systemic activity, and good activity on both pome and stone fruits (Avidan and Erez, 1995; Blanco, 1988; Edgerton, 1986; Facteau and Chestnut, 1991; Tukey, 1983; Williams and Edgerton, 1983; Williams et al., 1986). Unlike most other PGRs, foliar absorption and translocation of the triazole PGRs is generally minimal (Williams et al., 1986), although it does occur (Craighton et al., 1990) and will result in growth suppression when properly timed (El-Khoreiby et al., 1990) and directed (Lehman et al., 1990). The triazoles

are absorbed primarily through stem, bark, and root tissue (Davis and Curry, 1991; Tukey, 1983). Early studies with foliar sprays of 3000 to 8000 $mg \cdot L^{-1}$ paclobutrazol resulted in growth suppression on apple lasting 2 to 4 years after treatment (Greene, 1986; Tukey, 1983). Soil applied paclobutrazol, at rates below that used for foliar sprays, also produced residual activity, but generally of less duration than foliar sprays (Williams and Edgerton, 1983). Response to soil applications on peach and cherry occurred in the year of treatment, but on apple response was not evident until the year following treatment (Curry and Williams, 1986; Edgerton, 1986; Tukey, 1983). In studies with peach (Blanco, 1988; Ogata et al., 1989) and pear (Embree et al., 1987), when the growth retarding effect was lost, growth of trees previously treated with paclobutrazol was greater than the untreated trees. This response is similar to that reported for daminozide (Miller, 1988).

The strong residual and systemic effects provided a degree of unpredictability in the use of triazoles and were of concern during the label registration process for these materials. Later studies demonstrated that multiple low-rate foliar sprays were sufficiently effective and more consistent in suppressing vegetative growth (Estabrooks, 1993; Greene, 1991) compared to soil applications or high-rate foliar sprays. Less persistent triazole derivatives have been investigated as possible growth retardants that would avoid the residual problems associated with materials like paclobutrazol (Curry and Reed, 1989). Miller (1988) reviewed the work on paclobutrazol in apple and pear, and Davis and Curry (1991) later provided an additional review of the triazoles on pome and stone fruit. At the present time, paclobutrazol is labeled in several countries for growth control in apple and stone fruits, but the triazoles have not received registration for use in the U.S.

In 1990 the deciduous tree fruit industry was without a registered PGR material for use in suppressing excess vegetative growth, with the exception of ethephon; this despite the strong growth retarding effect achieved by the various GA biosynthesis inhibitors and the commercial success of some of these materials. In 1990, a new growth retardant with anti-GA activity was reported on rice (Nakayama et al., 1990). The material was from a class of growth retardants, the acylcyclohexanediones, with the common name prohexadione-calcium (3-oxido-4-propionyl-5-oxo-3-cyclohexene-carboxylate). The mode of action of prohexadione-Ca is to block the conversion of gibberellin A_{20} (inactive) to gibberellin A_1 (active), thereby reducing shoot elongation (Evans et al., 1999; Rademacher, 1993). Prohexadione-Ca is absorbed by the foliage with maximum uptake in about 8 hours, and moves acropetally to the growing points of individual shoots (Evans et al., 1999). Shoot growth responds to prohexadione-Ca about 2 weeks after application (Greene, 1999) with activity lasting for 3 to 4 weeks (Schupp et al., 2001; Unrath, 1999). The half life of prohexadione-Ca in the plant is about 14 days before degrading to the naturally occurring propane-1,2,3-tricarboxylic acid (Evans et al., 1999). In field tests, prohexadione-Ca has shown no carry over effects on apple (Miller, 2002). The half-life of prohexadione-Ca in soil is less than 7 days with decomposition mostly to CO_2 (Evans et al., 1999). In greenhouse tests on apple, GA_{4+7} sprays reversed the growth suppressing effect of prohexadione-Ca (Guak et al., 2001).

The growth controlling effect of prohexadione-Ca on apple trees was first reported in 1996 (Greene, 1996 a, b). These studies showed that a foliar spray of prohexadione-Ca was an effective growth

inhibitor over a range of concentrations from 125 to 375 mg·L^{-1} when applied to several apple cultivars. Greene (1996, 1999) observed a linear increase in fruit set with increasing concentration and at the highest rate (375 mg·L^{-1}) fruit set was nearly doubled on 'McIntosh' trees. Unrath (1999) confirmed the growth retarding effect of prohexadione-Ca on 'Delicious' apple trees over a similar concentration range and found equal response when applied between PF and 20 days after petal fall (DAPF). Unrath (1999) also observed an increase in fruit set by treatment at 0, 7, and 14 DAPF, but not at 21 DAPF. Miller (2002) reported four successive sprays at 50 mg·L^{-1} applied at weekly intervals beginning at PF provided growth control equal to that of a single spray at rates ranging from 125 to 375 mg·L^{-1} on 'Delicious' apple trees. Additional reports have suggested that multiple applications provide better growth control than a single application (Byers and Yoder, 1999; Unrath, 1999). Byers (2000) reported an additive effect on growth suppression when prohexadione-Ca was combined with ethephon in the same spray.

In many apple growing regions, about 70% to 85% of the total seasonal growth is completed within the first 32 DAPF (Byers and Yoder, 1999; Unrath, 1999). Under these conditions, maximum growth suppression depends on controlling the first flush of growth. Miller (2002) reported that sprays applied 2 to 3-weeks after PF were less effective than sprays applied at PF or within 10 days of PF. Timing of the initial spray is more important than rate in achieving early growth suppression, but rate is also important for maximum season-long growth control (Miller, 2002). Recommendations are to apply the initial prohexadione-Ca spray when shoot growth is between 2.5 and 7.6 cm, which coincides with PF to about 10 DAPF (Greene and Autio, 2002; Schupp et al., 2001). An effective cumulative dose of 250 mg·L^{-1} active ingredient prohexadione-Ca applied as a single spray or in several low-rate sprays has generally produced season-long control of vigorous shoot growth in bearing trees (Greene, 1999; Miller, 2002; Schupp et al., 2001; Unrath, 1999) except when sprays were delayed beyond the effective period after PF (Byers and Yoder, 1999; Unrath, 1999). Miller (2002) found that under some very high vigor conditions, an effective cumulative dose of 500 mg·L^{-1} was necessary to achieve an acceptable level of growth suppression. When growing conditions (temperature and moisture) encourage renewed growth, single applications of prohexadione-Ca near PF may not provide satisfactory season-long growth control because of the transitory nature of prohexadione-Ca. Under these conditions, multiple spray applications have provided effective growth suppression (Byers and Yoder, 1999; Unrath, 1999). When shoots resumed growth in mid-season (July), a single spray at 125 mg·L^{-1} provided effective growth suppression. A similar response has been reported in pear (Elfving, 1999) and sweet cherry (S. Guak, personal communication). Experts agree that specific recommendations for the application of prohexadione-Ca to apple are difficult given the various growing conditions encountered, the effect of crop load on growth, and the non-persistent nature of the material (Greene and Autio, 2002; Ross Byers, personal communication).

Prohexadione-Ca has shown good growth control activity in pear (Costa et al., 2001; Elfving, 1999) and sweet cherry (Elfving and Visser, 2001), but the material is not registered for these crops at this time. Prohexadione-Ca was registered for the control of shoot growth in apple in 2000 in the U.S. under the trade name Apogee® and in several European countries under the name Regalis®.

Altering tree root physiology to affect vegetative growth

The size and form of tree shoots must be controlled, at least in part, by size, structure, and metabolic activity of the root system. Numerous studies have demonstrated that a root/shoot balance is maintained and that the balance will be restored if there is a departure from that balance, e.g. by pruning or herbivory. The mechanisms responsible for this balance include direct effects of water and mineral availability, as discussed previously, but also probably include synthesis, transport, and detection of PGSs. Plant growth substances produced in roots, particularly ethylene precursors and abscisic acid, have been implicated in mitigation of many plant responses to stress such as water deficiency, hypoxia, and high salinity (Jackson, 1993). The role of other PGSs from roots, such as cytokinins and gibberrellins, in tree shoot development is less clear and little is known about the impact of root management practices on PGS-mediated effects.

Root development and signals from roots can vary among fruit tree genotypes and environments to profoundly affect orchard productivity. Differences in hydraulic conductance have been observed between apple scion budded on different rootstocks with lower conductance and fewer, smaller xylem vessels on dwarfing rootstocks (Higgs and Jones, 1990). Soumelidou et al. (1994) found smaller vessel diameters in dwarfing than in semi-dwarfing apple rootstocks, possibly due to elevated auxin at the bud union of dwarfing rootstock. Subsequently poor supply of water and minerals to scion could then dwarf the scion. Sap flow was decreased by water stress more in 'Granny Smith' apple trees grafted on full dwarf rootstock (MARK) than on standard seedling rootstock (Hussein and McFarland, 1994).

Incomplete vascular connections that can affect shoot morphology have also been implicated in graft incompatibility between fruit tree scion and rootstock. Establishment of new phloem and xylem derivatives were delayed in pear/quince grafts which likely contributed to incompatibility (Ermel et al., 1997). In apricot (*Prunus armeniaca* L.) grafted on *Prunus cerasifera* Ehrh., incompatible grafts resulted from delayed and incomplete differentiation of vascular tissue (Errea et al., 1994). In other studies, diseases have been implicated in dwarfing processes of fruit trees. Grapefruit trees were dwarfed by citrus exocortis viroids that reduced the tree's ability to absorb or transport water (Moreshet et al., 1998). Nutrient absorption and processing also have been implicated in size control effects of apple rootstocks (Rogers and Booth, 1960).

Research has suggested that PGS signals from the roots can be responsible for control of shoot growth. Cytokinin in sap, produced by apple rootstocks may interact with other phytohormones produced by the shoot (e.g. auxin) so that the phytohormone *balance* influenced tree size and fruiting (Skene, 1975). In peach, cytokinin and auxin levels were greater in xylem sap of dwarf genotypes (Glenn and Scorza, 1992). Results from that study imply that hormone receptors rather than hormone concentrations were responsible for dwarfing. A clearer understanding of the physiological causes for root-induced dwarfing is needed to assist geneticists to develop germplasm of desired shoot growth patterns. Cultural practices such as restricting rooting volume with physical barriers or with competition have been used to control fruit tree size. Peach trees grown in the field with rooting volume restricted by fabric-lined trenches modified shoot development by reducing the length of primary shoots (Williamson et al. 1992). As with dwarfing rootstocks, the pro-

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cess of shoot control by restricted rooting volume is not well understood. Peach trees grown in smaller root volumes absorbed less nitrate over the growing season, even though a solution consisting of excess nutrients was available to the roots (Ran et al., 1994). They hypothesized that a root-produced signal (cytokinin) was associated with the root perception of container size, and the signal reduced tree growth to maintain nitrogen concentration in plant parts. Cytokinins have been found to be produced in root tips and to subsequently exert control over shoot growth in peach (Richards and Rowe, 1977a, b). Cytokinins produced by root tips also may be reduced by drying soil and may have acted as a root-produced signal to restrict stomatal opening and water use (Davies et al., 1987). An alternative to PGS control of shoot growth may be that physical effects of altered water potential, and reduced substrate (nutrient and water) reduced rates of enzyme reactions and growth (Boote, 1977).

Summary and Future Needs in Vegetative Growth Control

The need to manage excess vigor in deciduous fruit trees is associated with improved production efficiency and fruit quality. But excess vigor has a price (Elfving, 1988) and ultimately it is the need to reduce the economic impact that excess vegetative growth has on the tree and the orchard that must drive our pursuit to regulate growth.

As discussed in this review, there are many approaches to regulating growth, but to date none have proven to be universally successful or complete. Great benefit would result from improved knowledge of the PGS-related processes involved in rootstock/scion fruit tree interactions with different climatic and edaphic conditions. Advances in molecular biology and genetic engineering offer the potential for improving our understanding of plants and the ability to manipulate plant growth. It is not unrealistic to consider a "dwarfing" gene that could be inserted into the DNA of a desired peach cutivar producing a tree that would match a specific planting density. Recent advances by fruit tree breeders in developing growth habits adapted to high-density planting systems illustrate a promising approach. While rootstocks have provided apple growers with trees of reduced stature suited to a wide range of planting densities, they have been only partially successful in controlling excess growth. Poor anchorage and disease susceptibility are major disadvantages with most of the available dwarfing apple rootstocks. There is still a pressing need for dwarfing rootstocks compatible with peach, pear, plum, apricot, and even cherry, although the recent introductions for sweet cherry represent a significant advancement.

Pruning will continue to be used as a "stopgap" or "quick-fix" method of growth control because it can be easily applied, but pruning alone cannot be relied upon to effectively contain growth while maintaining annual production. Judicious pruning coupled with branch orientation offers a much better approach to growth control in many deciduous tree fruits. The benefits of summer pruning are associated more with fruit quality than growth control. In practice, summer pruning may produce economic losses rather than gains (Elfving, 1988). Root pruning is too variable, somewhat difficult to apply under many soil conditions, and often has adverse effects on fruit size. Root restriction, however, has shown good response and additional work is needed to better understand the effect on growth and tree physiology. A practical and economical solution to applying root restriction techniques to field grown trees should be developed. More research is needed to provide fundamental information on the quanti-

tative removal or restriction of roots relative to the entire root and shoot. With edaphic traits, phenological stage of seasonal development of the fruit tree should also be considered as cultural guidelines are developed for physical reduction of fruit tree roots.
It is possible that significant control of fruit tree growth could be obtained by improved management of fertilizers in orchards, including timing of fertilizer application.

Better understanding is needed about the plant-to-plant interaction between grass and tree or between trees that can account for reduced tree root growth. Experiments have demonstrated that hormones, including ethylene and cytokinins, may be involved in signal transduction from a P- or N-enriched soil to stimulate root growth. Improved knowledge of hormonal relationships could well assist efforts to manage tree shoot size by managing roots and even improve fertilization and irrigation management.

Cropping has effects on growth, but the full impact of cropping on carbon partitioning, growth, fruit abscission, and fruit quality is not well understood. A better understanding of these areas could allow researchers to develop practical models for predicting growth. Models could offer greater opportunities for applying growth controlling cultural practices in a more timely and efficient manner.

Beside rootstocks, PGRs continue to offer the most efficient and effective, as well as cost-effective (Elfving, 1988) technique for regulating shoot growth and controlling tree size. The recent development and registration of prohexadione-Ca, a non-persistent growth inhibitor, represents a major advancement in the search for effective growth controlling materials. There is still a great need for an effective PGR growth retardant for stone fruits, particularly peach. Unfortunately the development of new PGRs faces many risks and challenges (Rademacher and Bucci, 2002). Many of the needs and concerns identified in 1991 by Davis and Curry (1991) are applicable today. In many European fruit growing regions, PGRs are already not acceptable if growers wish to meet certain produce standards. A fundamental knowledge of the factors that regulate growth may lead to the development of natural plant hormones as PGRs for growth suppression. In addition, more information is needed on the economics of PGR use for growth control compared to other methods.

Because deciduous fruit trees will continue to be planted at higher densities in a wide variety of edaphic and climatic environments, there will be a continuing need for shoot growth control and means to achieve that control.

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Caula Beyl
Dept. of Plant & Soil Science
Alabama A&M University
P.O. Box 1208
Normal, AL 35762

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