Time of Root Pruning Influences Vegetative Growth, Fruit Size, Biennial Bearing, and Yield of 'Jonathan' Apple

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Abstract. 'Jonathan'/M.26 apple (*Malus domestics* Borkh.) trees were root-pruned annually on two sides, 60 cm from the trunk, to a depth of 40 cm for 6 years while dormant, at bloom, or in mid-June. Root pruning reduced terminal shoot growth by $\approx 30\%$ in 1985-89 with no influence in 1990. Cumulative yield was reduced by root pruning at bloom (14%) or mid-June (20%), and cumulative yield efficiency [$\text{kg}\cdot\text{cm}^{-2}$ trunk cross-sectional area) was reduced by root pruning with no difference among pruning times except in 1 year, where abundant moisture throughout the season appeared to negate the effect. The intensity of biennial bearing was reduced by root pruning with no relationships to time of pruning. Root pruning resulted in a decrease in large fruit and an increase in small fruit in 3 of the 6 years. A covariant analysis with yield showed that root pruning reduced average fruit size. Root-pruned trees produced firmer fruit with an increased soluble solids concentration and had less preharvest drop than nonpruned trees. Under severe drought conditions in 1988, root pruning reduced net photosynthesis and transpiration; supplemental water (57 liters $\cdot\text{week}^{-1}$) increased transpiration and fruit size at harvest.

With the loss of daminozide, some fruit growers have turned to root pruning to reduce preharvest drop, improve fruit color, and reduce excessive growth (Schupp and Ferree, 1987a, 1987b, 1988b). The best time to root-prune to achieve the desirable reductions in growth and preharvest drop and improvement in fruit quality and also minimize undesirable reductions in fruit size is still uncertain. Luthie (1974) and Schupp and Ferree (1987a, 1987b) recommended root pruning between March and mid-May to control excessive growth. Researchers in Switzerland (Schumacher, 1975; Schumacher et al., 1978) advocated root pruning in February and March and indicated that treatments in April or December did not produce the desired results. Root pruning later in the growing season, at June drop or preharvest, had no effect on growth and increased preharvest drop (Schupp and Ferree, 1987b). Thus, previous work does not clearly establish the optimum time to achieve the desirable and minimize the undesirable responses to root pruning.

Greenhouse studies on young apple trees showed that root-pruning dramatically reduced net photosynthesis (Pn), transpiration (E), and water potential (Geisler and Ferree, 1984; Schupp and Ferree, 1990). In other studies, cytokinin trunk injections were not effective in overcoming the reduction in growth caused by root pruning (Schupp and Ferree, 1988a). Field studies indicated that root pruning had no effect on leaf mineral nutrient levels (Schupp and Ferree, 1987b). Thus, of the most obvious functions of roots, i.e., supplying moisture, mineral nutrients, or cytokinins, it appears that root pruning primarily influences moisture levels in the plant.

The present study was established to see if clear advantage existed for pruning in the late dormant period (March), at full bloom (May), or in mid-June and whether the addition of a small amount of water to the soil could overcome some of the

negative attributes of root pruning, particularly the reduction in fruit size.

Materials and Methods

'Jonathan'/M.26 apple trees were planted in 1968 in a fine, loamy mixed mesic typic Fragiudalf soil in east-west rows at a spacing of 3.7×6.7 m with 2-m-wide herbicide strip and sod drive rows. The trees were trained as central leaders; dormant containment pruning was necessary to maintain tree height at 3.0 m and spread at 3.7 m. The fruitlets were chemically thinned annually as needed.

Beginning in 1985, trees were root-pruned annually to a depth of 40 cm on two sides, 60 cm from the trunk, parallel to the rows at the following times: dormant (normally late March before growth started and after soil had thawed); full bloom (early May); mid-June; and nonpruned controls. Roots were pruned with a sharpened subsoiler mounted on a tool bar and offset to one side of a tractor (Schupp and Ferree, 1987a). Half of the trees had a small soil dike ($100 \times 100 \times 15$ cm) created around them, and ≈ 57 liters of water was added weekly unless 25.4 mm of rain/week occurred beginning at full bloom and continuing until mid-July. The addition of water had no influence on any characteristic measured except in the drought year of 1988. Thus, except for those affected in 1988, the analysis was performed as a randomized complete block design with seven replications and two trees of each treatment in each replication. In 1988, a split plot design was used, with the addition of water as the whole plot and timing of root pruning as the split plot, with seven single-tree replications.

Trunk circumference, yield per tree, length of 20 shoots/tree, and weight of dropped fruit were recorded annually. At harvest each year, all fruit were counted and graded on an FMC weight sizer (FMC, San Jose, Calif.) that divided the fruit into the following size classes: ≥ 80 mm in diameter (box size 80-88); 79 to 73 mm (100-113); 72 to 57 mm (125-138). The fruit were graded according to commercial standards, and culled fruit

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Abbreviations: Pn, net photosynthesis, SSC, soluble solids concentration.

were removed and counted. An analysis of covariance was performed using yield of fruit ≤ 80 mm in diameter and ≥ 72 mm in diameter as the covariant to determine treatment effects on fruit size. Bienniality was assessed on yields for 1985-86, 1986-87, 1987-88, 1988-89, and 1989-90 using the *i* index of Hoblyn et al. (1936), and these values were also combined into an overall mean bienniality index for the six years.

In 1985 and 1986, a sample of 10 fruit/tree (73 to 80-mm-diameter class) was taken, fruit firmness was measured on two sides of each fruit with a pressure tester (Effegi, McCormick Fruit Tech, Yakima, Wash.), and soluble solids concentration (SSC) with a refractometer (Bausch and Lomb Model Abbe-3L, Rochester, N.Y.). Fruit color was rated by comparing each fruit to a color photograph standard using 1 = 100% red to 5 = $\leq 40\%$ red scale.

Pn and E were measured four times in 1988 and three times in 1989, from late June to late July, with a portable infrared gas analyzer (Analytical Development Co. Model LCA-2 with a 6.25 cm² Parkinson leaf chamber; Hoddesdon, England). Air flow was regulated at 300 ml·min⁻¹, and ambient CO₂ concentration, humidity of the air entering and leaving the leaf chamber, the chamber temperature, and incident level of photosynthetically active radiation was taken with each measurement. Measurements were taken on the youngest fully expanded shoot leaf from a well-exposed position of the canopy between 9:30 AM and 12:00 AM.

Results and Discussion

Root pruning reduced annual shoot length growth by $\approx 30\%$ in 1985-89 with no influence in 1990 (Fig. 1). Timing of treatments had no significant effect. During the period of this study, Ohio experienced the driest season on record (1988) and the wettest (1990). In 1988, shoot length was reduced by 25%, which was common for this experiment and others using root pruning to control growth (Schupp and Ferree, 1987b, 1988b). In 1990, when the expected reduction in shoot length did not occur, rainfall exceeded 62 mm each month of the growing season, and in 5 of those 7 months, it exceeded 114 mm. Greenhouse studies conducted under conditions of consistently adequate moisture showed that root pruning caused dramatic short-term reductions in shoot growth rate, E, stomatal conductance, and water potential that recovered to normal in 3 to 4 weeks (Geisler and Ferree, 1984; Schupp and Ferree, 1990). Previous field studies have shown a consistent season-long reduction in

Fig. 1. Influence of time of root pruning on average shoot length of 'Jonathan'/M.26 apple trees over 6 years. Mean separation by Duncan's multiple range test, $P = 0.05$. Each mean contains 14 observations.

shoot growth (Schupp and Ferree, 1987a, 1987b, 1988b). Results from this study imply that the growth-controlling effect of root pruning in the field can be negated by abundant soil moisture.

Root pruning during the late dormant period in 1985 or mid-June 1987 resulted in a reduction in yield per tree, while all times of root pruning reduced yield in 1986 and 1988 (Fig. 2). In 1989, trees root-pruned in mid-June had higher yields than nonpruned trees. In 1990, with abundant moisture, there was no effect of treatment on yield. Previous work with 'Mel rose', a cultivar with large fruit, indicated no influence of root pruning at full bloom on yield (Schupp and Ferree, 1987b, 1988b); however, other studies have shown yield reductions (Brunner and Droba, 1980; Schumacher, 1975; Schupp, 1990; Scibisz, 1990). Results from the current study indicate that yield per tree on a cultivar such as 'Jonathan', which tends to have small fruit, can be reduced by root pruning, particularly in years when the nonpruned trees have high yields (1986 and 1988).

The intensity of bienniality was reduced by one or more of the root-pruning treatments in every 2-year comparison, except 1986-87 (Fig. 3). An average over all years produced the following *i* values and shows a clear effect for root pruning to reduce the biennial habit: control, 0.22a; dormant, 0.14b; full bloom, 0.11b; and mid-June, 0.11b.

Past studies (Schupp, 1990; Schupp and Ferree, 1987b, 1988b; Schumacher, 1975; Schumacher et al., 1978) have shown a

Fig. 2. Influence of time of root pruning on yield per tree of 'Jonathan'/M.26 apples over 6 years. Mean separation by Duncan's multiple range test, $P = 0.05$. Each mean contains 14 observations.

Fig. 3. Influence of time of root pruning on the intensity of bienniality (*i*) of 'Jonathan'/M.26 apple yields over 6 years. $i = (\text{yield year 1}) - (\text{yield year 2}) / (\text{yield year 1} + (\text{yield year 2}))$ (Hoblyn et al., 1936).

reduction in fruit size on root-pruned trees, while other studies have reported an increase (Brunner and Droba, 1980) or no effect (Elfving et al., 1991; Scibsz, 1990). In the present study, the weight of 'Jonathan' fruit ≥ 80 mm was decreased by root pruning in three of the six years (Fig. 4a). There was no difference due to time of root pruning in those three years. For 73 to 79-mm-diameter fruit, root pruning reduced the weight per tree in four of the six years (Fig. 4b), and in three of those four years, time of root pruning had no effect. Fruit weight per tree for 57- to 72-mm-diameter fruit tended to be increased by root pruning, with the effect significant for all treatments in 1989 and for two treatments in 1985 and 1987 (Fig. 4c). The weight of cull fruit per tree was generally decreased by root pruning in four of the six years of the study (Fig. 4d). In an attempt to separate the effects of yield from the effect of root pruning on fruit size, a covariance analysis was conducted that shows clearly that there was a root-pruning effect on fruit larger than 80 mm and those smaller than 72 mm and that it was independent of the effect of yield (Table 1). In 1990, with abundant moisture, when root pruning did not cause the expected reduction in shoot length, fruit size and yield per tree also were not affected.

Cumulative yield was reduced by root pruning at full bloom or in mid-June, and cumulative yield efficiency (yield per trunk cross-sectional area) was reduced by root pruning in mid-June (Table 2). Previous work from a single year on a large-fruited cultivar showed no influence of root pruning in June on yield or yield efficiency (Schupp and Ferree, 1987b). There was no relationship between time of root pruning and cumulative yield ($r = 0.12$) or cumulative yield efficiency ($r = 0.02$).

Fruit quality was measured in 2 years of the study; root pruning tended to increase color, fruit firmness, and SSC, but the differences were not significant in some cases. Preharvest fruit drop was reduced by root pruning in three of the five years it was measured. The improvement in fruit quality and reduction in preharvest drop with root pruning confirm previous findings on the effects of root pruning, although the effect was not always present each year in the various studies (Brunner and Droba, 1980; Elfving et al., 1991; Schumacher et al., 1978; Schupp, 1990; Schupp and Ferree, 1987b, 1988b).

One of the primary objectives of this study was to better define the best time to root-prune to produce the desired reduction in growth and minimize adverse effects on fruiting and yield. Researchers in Switzerland (Schumacher, 1975; Schumacher et al., 1978) advocated pruning from the beginning of December to the beginning of March and indicated that treatments in April did not produce the desired results. In previous work in Ohio, Schupp and Ferree (1987b) found that root pruning at June drop (23 June) had no influence on shoot growth and increased preharvest drop compared to pruning at bloom or in the dormant period. In the present study, there was no difference in the three times of root pruning on shoot length, and the effects on yield and fruit size were minor and not consistent. Thus, it appears that the window for acceptable responses is rather broad and extends from dormancy through mid-June.

In 1988, with a severe drought occurring early in the season, measurements of Pn and E were begun on 24 June and continued weekly until after significant rain fell in mid-July. Rates of Pn were relatively low, but root pruning or supplemental water had no influence on them, except on 8 July when supplemental water increased Pn [10.3 (water), 8.9 (control) $\mu\text{mol CO}_2/\text{m}^2$ per sec], and the nonpruned controls had a higher Pn than any of those root-pruned, which did not differ from each other [11.4 (control), 9.5 (dormant), 9.0 (bloom), 8.7 (June) $\mu\text{mol CO}_2/\text{m}^2$ per

Fig. 4. Influence of time of root pruning on the weight per tree of fruit in the following diameter size classes: (a) ≥ 80 mm; (b) 73–79 mm; (c) 57–72 mm; (d) culls. Mean separation by Duncan's multiple range test, $P = 0.05$. Each mean contains 14 observations.

Table 1. F significance levels from an analysis of covariance² of yield of two size classes of 'Jonathan' apple and timing of root pruning using total yield as covariant.

Variant	F significance (level)						
	1985	1986	1987	1988	1989	1990	Total
Large fruit (≥ 80 mm diam)							
Yield	0.0032	0.0280	0.4930	0.0651	0.0257	0.0073	0.2342
Root-pruned	0.0001	0.0044	0.4019	0.0539	0.2896	0.7449	0.0004
Yield $\times$ root-pruned	0.5293	0.8314	0.3415	0.3273	0.3217	0.0147	0.3267
Small fruit (≤ 72 mm diam)							
Yield	0.2660	0.0061	0.4091	0.0102	0.0218	0.0131	0.8912
Root-pruned	0.0001	0.0236	0.0064	0.0259	0.0971	0.5303	0.0108
Yield $\times$ root-pruned	0.2629	0.7307	0.7020	0.5838	0.4104	0.1574	0.4334

²Processed using SAS type 1 sum of squares.

Table 2. Influence of time of root pruning on cumulative yield, fruit quality, and preharvest drop of 'Jonathan' apples.

Time of root pruning	Cumulative yield		Color rating ²		Fruit firmness (N)		Fruit SSC (%)		Preharvest fruit drop (kg/tree)				
	kg/tree	kg·cm ^{-2y}	1985	1986	1985	1986	1985	1986	1985	1987	1988	1989	1990
Control	564.1 a ^x	1.76 a	2.5 a	2.5 a	31.5 b	56.3 b	14.2 b	14.3 b	12.9	28.2 a	19.6 a	4.4	7.3 a
Dormant	519.7 ab	1.62 ab	1.8 b	1.6 b	32.9 a	58.2 ab	15.0 a	14.5 b	8.2	14.1 b	10.1 b	6.3	5.9 ab
Full bloom	488.3 b	1.60 ab	2.2 ab	1.8 b	33.4 a	58.9 a	14.9 a	15.0 ab	7.2	13.6 b	9.7 b	4.2	5.9 ab
Mid-June	456.1 b	1.54 b	2.1 ab	1.7 b	30.0 c	60.1 a	15.2 a	15.3 a	11.2	10.8 b	6.1 b	3.3	4.5 b

^xColor rating: 1 = 100% red to 5 = <40% red.

^yYield per trunk cross-sectional area.

²Mean separation in columns within a year by Duncan's multiple range test, $P = 0.05$. Each mean contains 14 observations.

see]. On 24 June (3 days) after the June root pruning, E was reduced compared to the nonpruned trees but did not differ from those root-pruned earlier (Table 3). The same pattern existed on 1 July, and by July 8, all root-pruning treatments resulted in lower E levels than in nonpruned controls. On 22 July, several days after significant rain fell, E values were much higher than earlier and there were no differences among treatments. In 1989, a year of adequate rainfall, three measurements were made during the same period as in 1988 and levels of Pn and E were similar at all times. Previous work with greenhouse-grown trees showed significant reductions in Pn, E, and water potential immediately following root pruning, with recovery to control levels in ≈ 4 weeks (Geisler and Ferree, 1984; Schupp and Ferree, 1990).

Funt (1988) and Kenworthy (1972) suggested that apple trees the size of those used in this study would use from 40 to 100 liters of water/day under conditions of high evaporative demand. It is surprising that the addition of 57 liters of water/week in

the drought year of 1988 resulted in an increase in E on 24 June and 8 July. Supplemental water also increased the amount of fruit in the ≤ 80 -mm-diameter size class and decreased the amount in the 57- to 72-mm size class. There was no other effect of supplemental water in 1988 or in any other year of the study on any other variable measured, and the interaction between root pruning and supplemental water was never significant.

Results over the six years of this study show a consistent reduction in shoot length and fruit size due to root pruning, except in years when abundant moisture throughout the growing season may negate the effect. Root pruning reduced the tendency for biennial bearing and generally reduced preharvest fruit drop. There was little difference in response to pruning due to time that extended from dormancy through mid-June; thus, the window for growers to use the technique is wide. The only indication that it might be preferable to root-prune early during this window was the decline in cumulative yield and yield efficiency when pruning was delayed to mid-June.

Table 3. Influence of supplemental water and time of root pruning on E and distribution of fruit size of 'Jonathan' apple during the drought of 1988.

Variable	E ($\mu\text{g H}_2\text{O/m}^2$ per sec)				Fruit diam ranges (mm)					
	24 June	1 July	8 July	12 July	<80	80–73	73–57	>57	Culls	Total
					(kg/tree)					
Supplemental water										
Control	5.2 b ^z	4.30	5.77 b	8.19	3.5 b	21.4	60.8 a	5.3	10.4	101.7
Water (57 liters·week ⁻¹)	5.80 a	4.38	6.27 a	8.13	4.6 a	22.9	51.3 b	4.9	10.9	94.8
Time of root pruning										
Control	5.88 a	4.66	6.97 a	8.35	5.8 a	29.3 a	57.4	8.2 a	14.6 a	115.7 a
Dormant	5.68 ab	4.27	5.69 b	7.97	3.6 b	20.3 b	58.3	4.0 b	10.0 b	96.5 b
Full bloom	5.49 ab	4.73	5.91 b	8.27	3.0 b	18.7 b	59.4	4.2 b	8.5 b	94.0 b
Mid-June	5.16 b	4.13	5.49 b	8.08	3.7 b	20.2 b	49.3	4.0 b	9.5 b	86.7 b

²Mean separation for main effects in columns by Duncan's multiple range test, $P = 0.05$. Each mean for supplemental water contains 28 observations and for time of root pruning, 14 observations.

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