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Effect of Seasonal Soil Waterlogging on Vegetative Growth and Fruiting of Apple Trees

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Abstract. **Soil waterlogging imposed for 6-week periods in the spring, summer, or fall reduced vegetative growth and fruit yield of 'Macspur'/Malling 26 apple (*Malus domestica* Borkh.) trees over their 7th to 9th growing seasons. Shoot and trunk growth were reduced most by spring and summer waterlogging. The relative decrease in shoot growth of summer-waterlogged trees increased over the three treatment years. Excavation of the trees in 1985 revealed that root dry weight was reduced markedly by summer waterlogging, but shoot dry weight was not affected by treatment. Average fruit yield was reduced severely by spring waterlogging (52%). Yield reductions increased with successive years of stress for all treatments, with the most marked trend over years associated with summer waterlogging. Decrease in yield was paralled by increased return bloom. There were no marked effects on fruit quality.**

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Vegetative growth, fruit yield, and survival of fruit trees are reduced on wet, poorly drained soils (26). In humid regions, such as the northeast, temporary periods of soil waterlogging are common, especially in the spring (6, 11). Apples and other species are not affected if waterlogging is restricted to the dormant period (11, 16). In contrast, the tree is highly sensitive if similar conditions occur during the growing season (11, 16, 25, 26). Symptoms of severe waterlogging stress are reduction or cessation of shoot and root growth, injury, epinasty, senescence and abscission of leaves, root death, specialized adventitious root formation near the soil or water surface, lenticel proliferation on submerged root and stem, and shoot die-back or tree death (7, 16, 26). Physiological effects of waterlogging, such as reduction in photosynthesis (6), transpiration, and stomatal conductance (1, 6, 20), and changes in stem water potential (2) also have been observed in apple, pear, and quince, similar to other species (7, 16). Temporary periods of waterlogging may not result in obvious symptoms of stress or tree mortality, but concern has been expressed that long- and short-term reductions in yield and growth may result (6, 11, 26). Little data are available to evaluate this concern.

Soil waterlogging results in a number of component stresses, which can include low soil oxygen, phytotoxic accumulation of reduced ions, decrease in aerobic microorganisms (including mycorrhizal fungi), accumulation of phytotoxic by-products of anaerobes, and attack by water-borne pathogens such as *Phytophthora* and *Pythium* (7, 16, 23, 26, 28). Relative importance of these components varies with site conditions. Low soil oxygen is generally an important consequence of waterlogging. Apple is relatively tolerant to waterlogging compared to other temperate-zone fruit trees, generally less tolerant than pear and quince, and more tolerant than *Prunus* spp. (1, 26).

Small decreases in soil oxygen reduce vegetative growth of young apple trees (3–5). Formation of new roots in solution culture was most sensitive to oxygen depletion, followed by root elongation and, least sensitive, maintenance of existing roots (3, 5). However, O_2 concentration per se is poorly correlated with biological responses in soil (21). Availability of O_2 to a respiring root is not indicated simply by soil O_2 concentration, but is actually limited by the rate of O_2 diffussion through the soil. Oxygen diffusion rate (ODR) is a function both of the O_2 concentration gradient between the soil and root and of the path resistance to O_2 movement (largely determined by the diffusivity of O_2 in water for wet soils) (21). In general, root function begins to be limited when ODR falls to 0.3 to 0.4 and root death occurs when ODR is $<0.2\ \mu g \cdot cm^{-2} \cdot min^{-1}$ (27). Stomatal conductance of young pear and quince trees was reduced at ODR levels between 0.15 and 0.3 $\mu g \cdot cm^{-2} \cdot min^{-1}$ (1).

Most studies on effects of waterlogging and anaerobic root environments on apple have dealt with trees 1 to 2 years old. Reduction in stem growth has been noted in young apple trees after as little as 3 days to 1 month of waterlogging (1, 3, 11, 19, 20, 25). Severity and rate of response depends not only on the degree and duration of waterlogging stress but also on genotype (10, 25, 26), transpirational demand (11), and time of year (11, 15, 25). Injury was most severe and response time shortest when young trees were waterlogged during canopy development (11, 25). Cripps (8) found a reduction in total growth and an increase in shoot : root dry weight ratio when apple trees were waterlogged in the summer. One month of waterlogging in the fall reduced growth of young pear and apple trees the following spring.

Information regarding effects of waterlogging on apple trees of fruit-bearing age is extremely limited. Childers and White (6) flooded one 'Staymen Winesap'/French Crab tree in the field from 1 May to 8 June in one year (6th growing season) and compared the growth and fruiting of this tree to a similar, nonflooded tree over the year of treatment and for three subsequent years when neither tree was flooded. Smaller and fewer leaves, leaf injury, early leaf abscission, and lower yield and fruit set were noted for the flooded tree compared to the nonflooded tree in the treatment year. Return bloom was increased over the control the following spring. Fruit harvested from the flooded tree in the first year were small, highly colored, and matured and abscised early relative to the control, and total leaf dry weight and leaf area were lower in the flooded tree in all 4 years of the study. Total root dry weight was 48% less than the control in the 4th year after treatment. In another unreplicated study, surface and cortical corkiness of apple fruit were induced when a mature 'Northern Spy' tree was waterlogged for 1 year (12). There is no information for young or mature trees to determine whether effects of temporary waterlogging on growth and yield are increased, decreased, or unaffected by the number of suc-

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cessive years in which stress occurs. Similarly, the extent of recovery after seasonal waterlogging stress has been relieved needs to be evaluated.

The purposes of this study were: a) to determine the effect of time of year on response of growth and fruiting of apple to waterlogging under field conditions; b) to determine the extent of recovery in growth after temporary waterlogging has been relieved for the year; and c) to determine whether sensitivity of the growth and fruiting responses to temporary waterlogging are affected by the number of successive years in which stress is imposed.

Materials and Methods

Sixteen plastic-lined basins (1.5 m in diameter × 0.6 m deep) were dug into the soil and were planted with 'Macspur'/M 26 apple trees in 1976 at the Maine Agricultural Experiment Station Fruit Research Farm, Monmouth, by the New England Plant, Soil and Water Laboratory (ARS/USDA). The basins were filled with orchard soil to ground level. A manifold in the bottom of the basin allowed subsurface irrigation from, or drainage to, an adjacent well (≈1.0 m deep) where connection could be made to an irrigation line. 'Cortland'/M 26 were planted as a pollenizer guard row surrounding the experimental trees. The trees were trained to a central-leader form.

The present study was initiated in 1982, with four replications of four waterlogging treatments assigned in a randomized block design. Treatments were control (no waterlogging) or 6 weeks of waterlogging to the soil surface in the spring, summer, or fall. These treatments were imposed on the same trees from 1982–1984 to determine the effects of temporary waterlogging when repeated annually over several years. A 6-week period was selected, based on the typical period of high soil moisture observed during the spring growing season in Maine (data not shown). Average dates of the stress treatments were 29 Apr.–10 June (May–June period), 2 July–11 Aug. (July–August period), and 1 Sept.–15 Oct. (September–October period). When not waterlogged, the trees were irrigated from the soil surface to maintain soil water potential <50 kPa at a 20-cm depth. Average soil water potential of the controls was 30 kPa over the entire study. No differences in current season shoot growth, trunk cross-sectional area, or fruit yield were noted among treatment assignments in Fall 1981 (the year before treatments were imposed).

Bud development of 'McIntosh' to the "silver tip" stage occurred during the first week of April. Average bloom date occurred midway through the spring treatment period (average date, 22 May), terminal bud set occurred midway through the summer treatment period, the fruit were harvested midway through the fall treatment period (average date, 22 Sept.), and leaf abscission occurred during the last week of October, after the fall treatment period.

Soil O_2 diffusion rate was measured at a 20-cm depth at the end of each waterlogging period. Average ODR was determined from 10 platinum microelectrodes with an applied voltage of 0.65 V using a Jensen Instruments model C ODR meter (21).

Current season growth of five tagged shoots per tree and trunk circumference at 15 cm above the graft union was measured on all trees at the end of each waterlogging period. Treatment differences in leaf color were noted at the end of the fall waterlogging period and were rated visually (0 = 80–100%, 1 = 60–80%, 2 = 40–60%, 3 = 20–40%, and 4 = 0–20% of the canopy with green leaves).

Yield from each tree was recorded and average fruit diameter, fresh weight, soluble solids, flesh firmness, and a visual estimation of percentage of surface red color were determined from a 20-fruit subsample. Soluble solids content of expressed juice was determined from refractive index measured with a handheld refractometer. Flesh firmness was recorded as the force necessary to drive an 11-mm-diameter, round-ended piston to a depth of 9 mm. Following each treatment year, return bloom was determined by counting flower clusters on three tagged branches in each tree and expressing the counts relative to branch cross-sectional area. In 1983, final fruit load at harvest was expressed as the number of fruit on each tagged branch per branch cross-sectional area. More complete data on fruit load were obtained in 1984 by counting fruit on the tagged branches on four dates after bloom.

At the end of the study, soil surrounding each basin was removed with a backhoe on 20 and 25 June 1985. The soil within each basin then was removed carefully by hand, keeping as much of the root system intact as possible. After excavation, the root systems were photographed against a 20 × 20-cm grid. Finally, the trees were cut into segments and dried to constant weight at 70°C to obtain dry weight of the root system, aboveground stem tissue (trunk and branches), and combined leaves and young fruit.

Table 1. Mean soil oxygen diffusion rate, 1983–1984.

Treatment	Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$)[z] May–June	July–August	September–October
Control	0.48 a[y]	---	0.35 a
Spring	<u>0.09</u> b[x]	---	0.32 a
Summer	0.40 a	<u>0.12</u>	0.30 a
Fall	0.42 a	---	<u>0.16</u> b

[z]Soil oxygen diffusion rate was measured at a 20-cm depth at the end of each waterlogging period.

[y]Means within a column separated by Duncan's multiple range test, P = 5%.

[x]Underline denotes the treatment waterlogged within each waterlogging period.

Results

Treatment means. Controls remained in the nonstress range of ODR while waterlogging reduced ODR values to below 0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$ (Table 1). When stress was relieved for the year, the spring and summer treatments recovered to control ODR levels by the end of the September–October treatment period. Soil ODR was determined only for the summer treatment at the end of the July–August period, because the drier soils of the other treatments at that time precluded accurate measurements of ODR.

Current-season shoot growth and annual increase in trunk cross-sectional area were reduced by waterlogging (Table 2). Shoot growth continued after the spring treatment was released from waterlogging, but did not recover to control levels. Shoot growth did not continue after summer waterlogging. Annual trunk and shoot growth were reduced by an average of 41% from controls for the spring and summer treatments. Reduction of annual trunk and shoot growth by fall waterlogging was intermediate and not significantly different from either controls or the spring and summer treatments at the 5% level.

Excavation of the trees in June 1985 revealed that summer waterlogging decreased dry weight of leaves and young fruit by 48% and decreased root dry weight by 43%, but had no influ-

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Table 2. Mean effect of waterlogging on current-season shoot growth, annual increase in trunk cross-sectional area, and early leaf coloration for 1982–1984.

	Current-season shoot growth[z] (cm·yr^{-1})			Increase in trunk cross-sectional-area[x] (cm^{2}·yr^{-1})	Leaf color rating in
Treatment	May–June	July–August	September–October	September–October	mid-October[x]
Control	12.2 a[x]	24.5 a	24.1 a	3.7 a	1 c
Spring	9.3 ab[w]	15.7 b	15.8 b	2.5 b	0 c
Summer	7.6 b	12.4 b	12.4 b	1.9 b	2 b
Fall	9.7 ab	18.1 b	18.0 ab	2.8 ab	4 a

[z]Shoot growth was measured on the last day of each waterlogging period.
[y]Trunk area measured in mid-October.
[x]Differences in leaf color were noted at the end of the fall waterlogging period and were rated visually: 0 = 80–100%; 1 = 60–80%; 2 = 40–60%; 3 = 20–40%; and 4 = 0–20% of the canopy with green leaves.
[w]Means within a column separated by Duncan's multiple range test, P = 5%.
[v]Underline denotes the treatment waterlogged within each waterlogging period.

Table 3. Final dry weight of apple trees after three successive years of seasonal waterlogging.

	Dry wt (kg)[z]			Mean
Treatment	Shoot total	Leaves and fruit	Root system	shoot : root ratio
Control	4.6 a[y]	0.42 a	4.1 a	1.20 ab
Spring	3.7 a	0.38 a	3.3 ab	1.15 b
Summer	3.4 a	0.22 b	2.3 b	1.55 a
Fall	4.4 a	0.38 a	3.3 ab	1.36 ab

[z]Treatments applied in 1983–1984 and the trees were excavated in June 1985.
[y]Means within a column separated by Duncan's multiple range test, P = 5%.

ence on total shoot dry weight (Table 3). Reduction of root dry weight for spring- and fall-waterlogged trees was intermediate and not significantly different from either controls or the summer waterlogging treatment. Similar treatment differences were visually evident from the volume of root system excavated at the end of the study (Fig. 1). There was no effect of spring or fall waterlogging on dry weight of the combined leaves and fruit or of the total shoot. Waterlogging resulted in higher total shoot : root dry weight ratios for summer- than for spring-waterlogged trees. Shoot : root ratios of control and fall treatments were intermediate and not significantly different from either the summer or spring treatments.

Fruit yield and yield efficiency were reduced markedly by spring waterlogging over the three treatment years (Table 4). Spring waterlogging reduced yield per tree by 52% and yield efficiency by 42%. Reduction of yield and yield efficiency by summer and fall waterlogging were intermediate and not significantly different from controls or the spring flooding treatment. The effect of treatment on yield was well-correlated with fruit number, but not with fruit diameter or fresh weight (Table 4). Spring waterlogging increased return bloom by an average of 81% (Table 5). As with yield, the effects of summer and fall waterlogging on return bloom were intermediate and not significantly different from either controls or the spring waterlogging treatment.

Spring and fall waterlogging reduced fruit load per branch cross-sectional area at harvest by ≈60% (Table 5). Reduction in final fruit load by summer waterlogging was intermediate and not significantly different from controls or from the spring and fall treatments. Fruit load of spring-waterlogged trees was reduced drastically by the end of the spring treatment period (17 days after full bloom) in the 1984 time course (Fig. 2). Intermediate reductions in fruit set of the summer and fall treatments at the same time suggested residual effects of waterlogging from the previous year. From 33 days after full bloom through harvest, fruit load of all waterlogged treatments was less than controls.

Effects of waterlogging on fruit quality at harvest were minimal and not statistically significant, with average values across treatments for red surface color, flesh firmness, and soluble solids of 84%, 63 N, and 11.6%, respectively. Leaf senescence, rated visually on the last day of the fall treatment period, increased as waterlogging occurred late in the growing season (Table 2). These results suggest that fruit maturity and senescence were not affected in the same manner as leaf senescence.

Effects over years. Annual current-season shoot growth and fruit yield of control trees declined linearly over years during the course of the study (significant at the 5% level). Since growth and fruiting of controls varied with year, effects of waterlogging treatments over years were evaluated relative to control values. The negative trends of relative growth over years for summer waterlogging, and of relative fruit yield over years for all three waterlogging treatments, indicate that these treatment effects intensified with succeeding years (Fig. 3). In contrast, relative decrease in vegetative growth with spring and fall waterlogging was not affected by the number of treatment years. In no instance did stress periods in previous years reduce response to waterlogging.

Discussion

Decreased leaf and shoot growth are among the most sensitive plant responses to water stress (14). Reduction or cessation of vegetative growth is associated both with drought stress (17, 18, 22) and soil waterlogging (16, 26) in apple and other woody species. Many plant species that are well-adapted to wet sites

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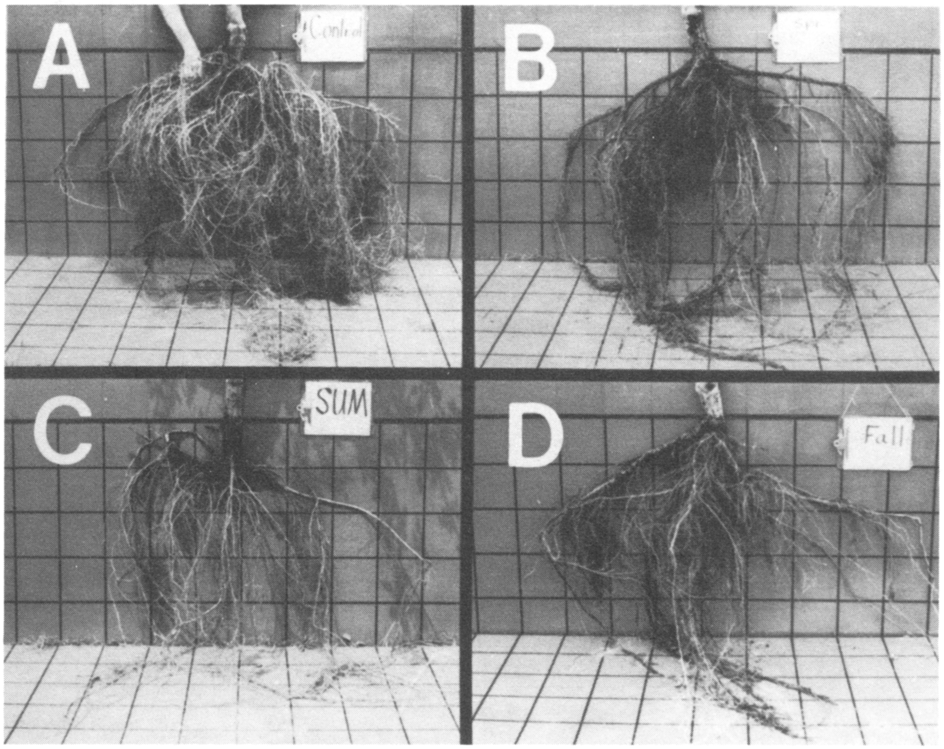

Fig. 1. Root systems typical of each waterlogging treatment, as excavated in 1985. Grids are 20 × 20 cm. The heavy line at the top of the grid represents the soil line. (**A**) Control. (**B**) Spring-waterlogged. (**C**) Summer-waterlogged. (**D**) Fall-waterlogged.

Table 4. Mean fruit yield, yield efficiency, and components of yield over 1982–1984.

Treatment	Yield (kg/tree)	Yield efficiency[z] (kg·cm^{-2})	Components of yield[y] No. fruit per tree	Fruit diam (cm)	Fresh wt per fruit (g)
Control	12.5 a[x]	0.60 a	100 a	6.7 a	148 a
Spring	6.0 b	0.35 b	59 a	6.5 ab	147 a
Summer	9.4 ab	0.55 ab	90 a	6.5 ab	118 a
Fall	8.4 ab	0.42 ab	86 a	6.4 b	120 a
Correlation with yield (n = 48):			+0.92	NS	NS

[z]Yield efficiency was calculated from yield per trunk cross-sectional area.
[y]Components of yield were determined from a subsample of 20 fruits collected at harvest.
[x]Means within a column separated by Duncan's multiple range test, P = 5%.

Table 5. Effect of seasonal waterlogging on harvest fruit load and return bloom the following year.

Treatment	Per branch cross-sectional area: Return bloom[z] (clusters/cm^2)	Final fruit load[y] (fruit/cm^2)
Control	9.7 b[x]	44 a
Spring	17.6 a	13 b
Summer	13.0 ab	26 ab
Fall	12.5 ab	21 b

[z]Return bloom was counted in May following each treatment year.
[y]Final fruit load counted at harvest.
[x]Means within a column separated by Duncan's multiple range test, P = 5%.

show reduced growth when waterlogged (7). This survival mechanism is one that reduces energy demanded from metabolism (7). The waterlogging treatments imposed in this study reduced vegetative growth rates of bearing apple trees, but severity of response depended on time of year (Table 2). Although the studies are not directly comparable, reported effects of waterlogging on growth of young apple and pear trees (1, 11) appear to be similar to effects reported here for older, fruiting apple trees.

Greater loss of root than shoot is a common response of plants to waterlogging (15). Summer waterlogging resulted in the greatest loss of roots and the largest shoot : root ratio (Table 3). Surviving roots and new adventitious roots are concentrated near the soil surface, weakening tree anchorage and making the tree more susceptible to drought stress later in the season (6, 16, 24). Lenticel proliferations were noted on the roots of waterlogged trees in this study, but new adventitious roots were not found when the trees were excavated. The presence of root rot was apparent when summer-waterlogged trees were dug, and likely contributed to the decline of these trees over the 3-year period. Typical symptoms of collar rot (*Phytophthora cactorum*)

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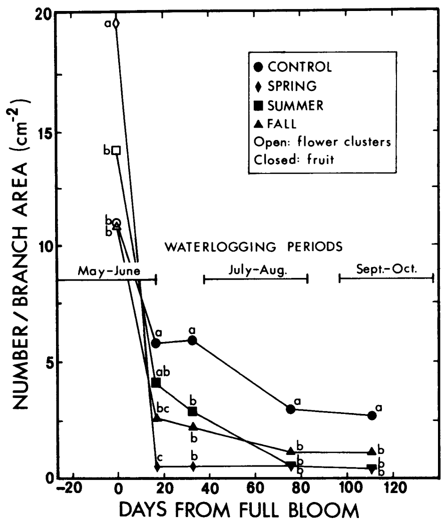

Fig. 2. Effect of waterlogging treatments on blossom cluster and fruit load through the 1984 season (3rd year of treatment). Full bloom occurred on 26 May (day 0), and harvest occurred on 21 Sept. (day 118). Means within a day separated by Duncan's multiple range test, $P = 5\%$.

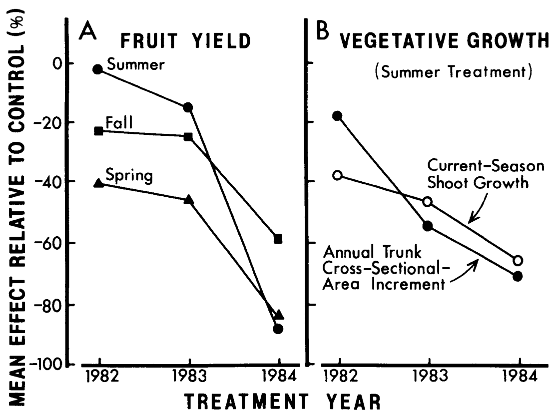

Fig. 3. Relative effect of waterlogging stress over three successive treatment years. All correlations were significantly different from zero at the 5% level. (**A**) Reduction in mean yield of spring-, summer-, and fall-waterlogged trees, relative to controls. Linear correlation of relative yield with years of treatment was -0.92, -0.93, and -0.90 for spring, summer, and fall waterlogging, respectively. (**B**) Reduction in means of current-season shoot growth and annual trunk cross-sectional area increment of summer-waterlogged trees, relative to controls. Linear correlation of relative growth with years of treatment was -0.98 for both shoot and trunk growth.

at or near the soil surface were not present. Leaf senescence was advanced moderately by summer and markedly by fall waterlogging. In cherry, early defoliation by cherry leaf spot reduced winterhardiness (13). Severe winters did not occur during this study, and winter injury was not observed in any of the treatments. However, the cherry study (13) suggests that early leaf senescence and abscission following waterlogging could increase risk of winter injury in some years, especially after fall waterlogging.

Treatment effects on increase in return bloom (Table 5) paralleled decrease in yield (spring treatment affected the most) (Table 4). The magnitude of reduction in fruit load and vegetative growth the previous season may explain the increases in return bloom. Reduced fruit load early in the season (Table 5; Fig. 2) may have been due to a direct effect of stress on flower and initial fruit development, or to indirect effects of waterlogging, generally weakening the tree and limiting the fruit load that the tree was capable of supporting. Marked effects on fruit quality were not noted in this study, in contrast to the report by Childers and White (6) for 'Stayman Winesap'.

Few studies have considered whether sensitivity of growth and yield to any temporary stress is affected when the stress is imposed in successive years. It is suggested frequently that a major effect of waterlogging stress is the induction of drought stress as a consequence of decreased root function (11, 26). Cumulative effects of drought stress over years have been observed on trunk circumference and shoot growth of apple (9, 15). In the present study, reduction in shoot growth of summer-waterlogged trees increased with successive years of stress (Fig. 3). Reduction in fruit yield increased over years for all three periods of waterlogging. While the largest total reduction in yield resulted from spring waterlogging, yield reductions of the spring and summer treatments were equal in the 3rd year (Fig. 3).

Rather than an injury in a physiological sense, reduced growth and yield of apple trees in response to waterlogging may be a stress-avoidance mechanism, increasing the chance of tree survival. However, severe, prolonged waterlogging is rare in typical orchards. Tree productivity and economic returns are reduced more by the effects of waterlogging on growth and fruit load than by actual loss of trees. Thus, reduction in growth and yield is the more important definition of injury in horticultural terms. A genotype that does not reduce growth and yield in response to temporary waterlogging periods would be expected to perform well under common orchard conditions. At the same time, such a genotype would likely have a higher-than-normal rate of mortality in excessively wet sites.

It is important to note that reductions in growth and yield occurred without obvious above-ground symptoms of waterlogging stress. A healthy appearance of trees is not a good index of whether growth and yield are limited by periods of excessive soil moisture in an orchard. One exception was early leaf coloration with fall waterlogging, although growth and yield were decreased least by this treatment (Tables 2 and 4). Overall, reduction in trunk and shoot growth by seasonal waterlogging can be ranked as: spring = summer > fall. Reduction in yield can be ranked as: spring > summer = fall. However, severity of response within any period can be increased by stress imposed in previous years. Further, effects of temporary waterlogging on growth and yield persist after stress has been relieved for the year. Thus, seasonal waterlogging can have long-term effects on productivity in apparently healthy orchards.

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