Benefits of Irrigation or Fertigation on Early Growth and Yield of a High-density Apple Planting in a Humid Climate

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ABSTRACT. The success of a new high-density apple planting depends on how fast the grower can recoup the high investment that these systems require. The right balance between vegetative growth and cropping during the early life of the planting is where tree growth is sufficient to rapidly fill the allotted space while at the same time producing high early yields. In this study we evaluated irrigation or fertigation as strategies compared with the traditional nonirrigated control to improve growth and yield of five apple scion cultivars (Mutsu, Gala, Honeycrisp, Jonagold, and Macoun) on M.9 or B.9 rootstocks over the first 5 years at Geneva, NY. Calcium nitrate at the rate of 113 kg·ha^{-1} N was applied to all three irrigation treatments (dissolved in water for the fertigation treatment, broadcast dry with the irrigation treatment, or broadcast dry with the nonirrigated control). Our results showed that fertigation with dissolved N and irrigation with dry broadcast N increased yield and tree growth similarly and significantly over the first 5 years of orchard establishment compared with the nonirrigated treatment with dry broadcast N. There was a significant economic benefit of irrigation or fertigation in the humid climate of New York State.

Early plant growth of apple trees (*Malus ×domestica* Borkh.) after transplanting to the orchard determines how quickly the tree can fill the allotted space and influences early fruit production. With low-density orchards, fruit trees must develop a strong tree structure in the early life of the orchard (years 1 through 4) to be able to support future crops beginning in year 5. However, with modern high-density plantings, which require high initial investments, it is expected that trees will grow sufficiently to fill the allotted space in the first 2 to 3 years while at the same time beginning fruit production in the second year to recoup the investment costs as quickly as possible (Robinson et al. 2007).

The Tall Spindle growing system (Robinson 2006; Robinson et al. 2008) is one of the most popular high-density orchard systems in the world. This system uses highly branched trees from the nursery (10 to 15 feathers) and minimal pruning for the first 3 years after planting while the tree is grown to the desired height of 3 to 3.3 m. The highly branched trees combined with precocious and dwarfing rootstocks and minimal pruning results in significant yield in the second to fifth years. However, some growers have experienced poor tree growth in the first few seasons, which limits second- and third-year yields.

A number of factors influence early tree growth and cropping including initial tree caliper (Robinson et al. 2004; Sadowski et al. 2007; Van Oosten 1976), initial number of lateral branches (Ferree and Rhodus 1987; Sanders 1993; Van Oosten 1976), water supply (Pereira and Pires 2011; Robinson and Stiles 1994, 2004), mineral nutrient reserves in the plant and new nutrient supply (Cheng and Fuchigami 2002; Stiles and Reid 1991), and crop load in the early years (Palmer 1992; Robinson 2008).

Irrigation has been used for centuries in drier environments where rainfall is inadequate to supply the crop needs for growth and productivity (Bravdo and Proebsting 1993); however, in humid regions of the United States, the use of irrigation is not yet been fully implemented. The main reason some fruit growers give for not using irrigation in New York State is they do not see the economic benefits it will bring to their operations (Robinson and Stiles 1994). However, even in humid climates, periods of drought can occur frequently in some years, affecting not only growth of young trees but also fruit production and quality in established orchards (Robinson et al. 2022). In modern high-density plantings, which use dwarfing and precocious rootstocks that have small root systems, dry weather shortly after planting can have a long-term negative effect on the trees growth and productive capacity (Parra-Quezada et al. 2008). This is in part because feathered trees have a large aboveground branch structure and experience considerable transplant shock when dormant transplanted to the orchard. Despite the risk of poor tree growth without irrigation, more than 80% of new plantings in the northeastern United States are not irrigated, which results in pronounced water stress in some years where natural water supply is not consistent.

In addition, mineral nutrients can be added to the irrigation water through fertigation. One of the potential advantages of fertigation is the potential for more close synchronization of nutrient application with plant demand (Haynes 1985). The nutrients are delivered directly to the root system; therefore, the uptake of minerals is potentially more efficient and nutrient leaching is limited (Robinson and Stiles 2004). The use of fertigation in the humid eastern part of the United States has not been fully adopted. This is due partly to previous studies done by Robinson and Stiles (1994) in New York that showed no improvement in growth or yield from fertigation, compared with drip irrigation with ground-applied fertilizers. Their trial compared ground-applied fertilizers without irrigation to ground-applied fertilizers plus irrigation with fertigation, using Oregon-Spur Delicious, Mutsu, and Empire apple cultivars. However average fruit size in that study was improved with the use of fertigation. In contrast, Bubán and Lakatos (2000) found that fertigation improved yield compared with the standard drip irrigation, but the irrigated trees had very similar growth to the

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fertigated trees. In semiarid climates there is considerable literature that compares the use of fertigation with broadcast application. Studies done in those conditions have focused on the advantages of nutrient movement and retention in the roots by the use of fertigation on sandy loam soils, especially for N, P, and K (Neilsen et al. 1999). This allows increased flexibility in the applications of the nutrients in response to plant demands and climatic conditions, which can help ensure good tree growth in the first few years.

The objective of this project was to assess the benefits of irrigation or fertigation to improve growth and yield of a new Tall Spindle orchard in New York State, which has a humid climate.

Materials and methods

Plant material

In 2009 an orchard was planted at the New York State Agricultural Experiment Station in Geneva, NY, USA (42°N, 77°W). The soil was a Honeoye fine sandy loam (He), with high water-holding capacity, well drained and fertile with about 3% organic matter content and a 6% slope. Five apple scion/rootstock combinations were used in this experiment: 'Mutsu' on M.9T337 rootstock, 'Brookfield Gala' on M.9Pajam2, 'Rubinstar Jonagold' on B.9, 'Honeycrisp' on M.9Nic29, and 'Macoun' on B.9. These main effect treatments are hereafter referred to as "Cultivar" effects using the monikers Mutsu, Gala, Jonagold, Honeycrisp, and Macoun with the recognition that they represent both scion and rootstock effects with respect to irrigation treatment response.

The trees were planted on 18 Apr 2009, at a spacing of 1 m within the rows and 3.5 m between rows (2857 trees/ha) and were trained as Tall Spindles. The orchard received standard disease, insect, and weed control throughout the five growing seasons. Crop load was managed each year as follows: in the second year, trees were hand thinned when fruitlets were 10 mm in size to a single fruit per cluster and then additional thinning was done to space the fruitlets to 10 cm between fruitlets. In the third through the fifth seasons, trees were chemically thinned when fruit size was 10 mm and then additional hand thinning was done when fruits were 25 mm leaving a single fruitlet per cluster and 10 cm between fruits.

Experimental design and treatment structure

The experiment was designed as a strip-split-plot, randomized complete block with the main plot treatment being cultivar (Mutsu, Gala, Honeycrisp, Jonagold, and Macoun) and the subplot treatments being three water management treatments. Each subplot was composed of five individual trees with a guard tree between each irrigation treatment. The three irrigation treatments were randomized within each cultivar. The experimental orchard was organized in five rows of 97 trees each (one row per cultivar) with rows oriented north-south. Blocking of subplot treatments within each cultivar was based on initial trunk diameter measured with a digital caliper. Cultivars were laid out as strip treatments to facilitate orchard management, especially chemical thinning.

We compared three water management treatments: irrigation, fertigation, and no irrigation, each with the same amount for N fertilizer. Calcium nitrate was used as the fertilizer at a rate of 113 $kg \cdot ha^{-1}$ N. The fertilizer for the fertigation treatment was dissolved in water and then applied through the drip line on a weekly basis. The fertigated total annual amount of N was divided into 10 equal amounts applied weekly (11.3 kg of N/week/ha) starting after budbreak each spring. For the irrigation treatment, $CaNO_3$ was manually applied to the soil surface in a circular-shaped band around each tree. The total annual amount of N was divided into two equal halves and applied at green tip and late June. Irrigation water was then applied weekly at the same times as the fertigation water. Additional water if needed was applied midweek without dissolved fertilizer. The amount of irrigation water applied each week was dependent on weather conditions and was the same for each cultivar. Daily temperature, solar radiation, amount of rain, and wind speed were measured and incorporated in an apple-specific evapotranspiration irrigation model (Dragoni and Lakso 2011) that estimated the amount of irrigation water needed in any given week. The weather data for each year are presented in Table 1.

In the nonirrigated treatment, $CaNO_3$ was manually applied to the soil in a similar manner and at the same timings as the irrigation treatment but with no irrigation. A guard tree of the same cultivar separated plots of each irrigation treatment to avoid cross-treatment contamination.

Measurements

Tree growth. Trunk circumference was measured at planting and in November of each year at 30 cm above the graft union and used to calculate trunk cross-sectional area (TCSA). Shoot growth was recorded in November each year for the first 4 years at the end of the season but was not recorded in the final fifth season. The length of every 1-year-old shoot on the tree including the axis was measured. This procedure was done in 2009, 2010, and 2011. However, in 2012, the methodology was different. The leader and 30 randomly chosen 1-year-old shoots were measured and the total number of shoots was counted on the whole tree. The number of shoots on the tree was multiplied by the average length of the 30 randomly chosen shoots to estimate total 1-year-old shoot length on the tree. In the spring of each year before budbreak for the first 4 years, the weight of the prunings per tree was recorded. In the second and third seasons, the number of floral buds at bloom and the number of spurs (shoots shorter than 10 cm) at the end of the season were counted.

Yield. During the first year, trees were not allowed to crop, but beginning in the second growing season the trees were allowed to crop and harvest data were collected annually. At each harvest, fruits were counted and weighed and the number of dropped apples was recorded.

Fruit quality. In the third and fourth years, a sample of 35 fruits was collected from each elemental plot of water management treatments and stored in refrigerated storage for 4 to 5 months with a temperature of 2 °C and a relative humidity of 75%. After storage, fruit disorders including as bitter pit, soft scald, water core, and senescent breakdown were assessed. In the fourth year, the 35-fruit storage sample was evaluated for fruit size and color using a commercial electronic MAF RODA Pomone fruit grader with a camera system for evaluating red color

Table 1. Weather data during the 5 years of this experiment at Geneva, NY, USA.

Year	Month	Maximum avg temp (°C)	Minimum avg temp (°C)	Precipitation (mm)	Pan evaporation (mm)
2009	April	14	2	40	—[i]
	May	20	7	89	148
	June	23	12	122	158
	July	24	14	92	164
	August	26	15	83	149
	September	22	11	44	117
	October	13	5	90	60
	Seasonal total first year	**Average = 20**	**Average = 10**	**Total = 560**	**Total = 796**
2010	April	17	4	47	—
	May	22	10	65	139
	June	25	15	168	163
	July	28	17	131	188
	August	26	16	114	145
	September	22	11	70	107
	October	15	7	161	85
	Seasonal total second year	**Average = 22**	**Average = 11**	**Total = 755**	**Total = 826**
2011	April	13	3	162	—
	May	20	10	115	41
	June	25	15	59	182
	July	29	18	18	229
	August	26	16	174	146
	September	22	13	112	61
	October	15	6	129	67
	Seasonal total third year	**Average = 22**	**Average = 11**	**Total = 768**	**Total = 726**
2012	April	12	2	61	—
	May	23	11	64	175
	June	23	13	66	178
	July	29	18	71	203
	August	27	15	57	161
	September	23	10	50	121
	October	16	7	124	64
	Seasonal total fourth year	**Average = 22**	**Average = 11**	**Total = 493**	**Total = 903**
2013	April	13	1	80	—
	May	22	9	97	138
	June	24	14	147	155
	July	27	17	119	168
	August	25	15	103	151
	September	21	10	47	111
	October	17	7	85	68
	Seasonal total fifth year	**Average = 21**	**Average = 10**	**Total = 678**	**Total = 790**

[i] Source: NY State Agricultural Experiment Station Weather station accessible at www.newa.cornell.edu. Pan evaporation was not recorded in April of each year. The date of budbreak varied each year with the earliest date in 2012 (22 Mar) and the latest date in 2011 (15 Apr). Harvest began in early September with Gala and Honeycrisp and ended with Mutsu on 15 Oct each year.

and load cells for evaluating fruit weight. A random subsample of 10 apples was tested for soluble solids concentration (percent) using a portable refractometer (Atago), fruit firmness was measured from two peeled sides at the equator of each fruit using a fruit penetrometer (Pressure Tester, Model EPT-1; Lake City Technical Products Inc., Kelowna, BC, Canada). Fruit dry matter content was evaluated by measuring fresh and dry weight of 20 longitudinal slices from the 10 apples in the sample (two from each apple).

We calculated the gross cumulative crop value for each treatment by multiplying the cumulative production (t/ha) by the typical fruit price per kg for each cultivar ($0.65/kg for Mutsu, Gala, Jonagold, and Macoun and $1.3/kg for Honeycrisp).

Leaf nutrient levels. In early August of the first 2 years, a 50-leaf sample was collected from midposition leaves on extension shoots of the three center trees in each water management treatment subplot of five trees. Leaves were dried, ground, and analyzed for macro- and micronutrients at a commercial laboratory (A&L Great Lakes Laboratory, Fort Wayne, IN, USA) using combustion and inductive coupling plasma-spectrometry (ICP).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) with a strip-split-plot design where cultivar was the main plot and water management treatment was the subplot factor. Where ANOVA indicated a significant cultivar or water management treatment effect, mean separation was done by Duncan's multiple range test with $P \leq 0.05$ and the appropriate error term for cultivar (main plot error) or water management treatment and the interaction of cultivar and water management treatment (subplot error).

Results

Vegetative growth. During the first year (2009), the fertigation treatment increased TCSA and tree height the most, followed by the irrigation treatment and lastly by the unirrigated treatment (Table 2). Fertigation and irrigation increased leader length, total shoot length, average shoot length, pruning weight, and total tree length similarly and significantly more than the unirrigated control. There was a significant interaction of cultivar and water management treatment in total shoot length in which fertigation and irrigation with Mutsu, Gala, Honeycrisp, and Macoun gave similar but significantly higher total shoot length than the unirrigated control. However, with Jonagold, fertigation gave greater total shoot length than the irrigation treatment and in turn the irrigation treatment increased total shoot length significantly more than the control. Pruning weight also showed a significant interaction, with Mutsu, where fertigation resulted in increased pruning weight compared with the irrigation treatment, which in turn had significantly greater pruning weight than the control. With Gala, fertigation and irrigation had similar pruning weights but significantly greater than the control. In the case of Jonagold, the irrigation treatment had significantly greater pruning weight than fertigation and the unirrigated control, which were similar. Honeycrisp and Macoun did not show any differences in pruning weight between the water management treatments.

In the second year of growth (2010), the fertigation and irrigation treatments increased TCSA, total shoot length, spur number per tree, pruning weight, number of spurs, and number of limbs pruned per tree and total tree length similarly and significantly compared with the unirrigated treatment (Table 3). Fertigation increased average shoot length, whereas the irrigation treatment was not significantly different from the control.

The interaction of cultivar and irrigation treatment was significant with three response variables in 2010 (Table 3). With total shoot length, fertigation and irrigation gave similar responses and were significantly higher than the control with Gala and Honeycrisp. However, with Mutsu, Jonagold, and Macoun there were no significant differences between the treatments. With average shoot length, fertigation and irrigation gave a significantly greater shoot length than the control with Mutsu. However, with Gala, average shoot length was greatest with the unirrigated control and the fertigation treatment being significantly greater than the irrigation treatment. With Honeycrisp, Jonagold, and Macoun, there were no significance differences among the treatments. Last, fertigation and irrigation had a similar effect on total tree length and were significantly more than the unirrigated control for Mutsu, Gala, and Honeycrisp. With Jonagold and Macoun there were no differences between the treatments.

During the third year of growth (2011) fertigation and irrigation similarly increased TCSA, pruning weight, number of spurs and limbs pruned per tree, and the total tree length compared with the unirrigated control treatment (Table 4). The irrigation treatment and the unirrigated control increased leader length and average shoot length similarly; however, only irrigation was significantly different from the fertigation treatment. Total shoot length was increased the most by irrigation, followed by fertigation and last by the unirrigated control, all treatments being significantly different from each other.

In 2011 there were four response variables in which the interaction between cultivar and irrigation treatment was significant (Table 4). With leader length there was no significant difference with Mutsu, Gala, or Macoun, but for Honeycrisp fertigation increased leader length significant greater than the unirrigated control, and for Jonagold the unirrigated control and irrigation treatment increased leader length significantly more than the fertigation treatment. A second interaction resulted with Mutsu and

Table 2. Effect of irrigation and fertigation on tree growth of five apple cultivars during the first year (2009) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	TCSA (cm^2)	Tree height (cm)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Spur no. per tree	Pruning wt (g)	Total tree length (cm)
Main effect means									
Mutsu/M.9T337		4.6 a[i]	192 b	33.4 b	249 c	20.6 b	15.7 c	11.6 b	595 c
Gala/M.9Pajam2		4.3 b	210 a	39.3 a	471 a	21.3 b	25.1 b	17.6 a	964 a
Honeycrisp/M.9Nic29		3.8 c	196 b	37.5 ab	256 bc	13.7 c	43.0 a	0.8 c	608 c
Jonagold/B.9		4.1 bc	180 c	40.0 a	287 b	24.2 a	17.8 c	9.1 b	672 b
Macoun/B.9		3.6 d	165 d	41.6 a	205 d	21.0 b	18.3 c	1.7 c	415 d
Cultivar/stock significance		**	**	**	**	**	**	**	**
	Unirrigated	3.5 c	182 c	32.0 b	198 b	15.1 b	25.1	3.0 b	559 b
	Irrigated	4.2 b	190 b	40.7 a	329 a	22.2 a	23.4	10.9 a	683 a
	Fertigated	4.5 a	194 a	42.4 a	355 a	23.1 a	23.6	10.6 a	703 a
Irrigation treatment significance		**	**	**	**	**	NS	**	**
Interaction significance		NS	NS	NS	*	NS	NS	**	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
*, **, or NS indicates treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Table 3. Effect of irrigation and fertigation on tree growth of five apple cultivars in the second year (2010) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	TCSA (cm^2)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Spur no. per tree	Pruning wt (g)	Spurs pruned per tree	Limbs pruned per tree	Total tree length (cm)
Main effect means										
Mutsu/M.9T337		8.8 b[i]	42.3 b	659 cd	23.7 b	37.1 b	101.4 b	7.4 b	0.58 ab	908 cd
Gala/M.9Pajam2		10.5 a	57.2 a	1423 a	31.4 a	62.8 a	305.2 a	12.2 a	0.64 ab	1894 a
Honeycrisp/M.9Nic29		7.9 c	29.1 c	1089 b	20.7 b	45.7 b	92.5 b	8.1 b	0.42 b	1345 b
Jonagold/B.9		7.9 c	46.4 b	791 c	30.5 a	37.0 b	141.2 b	6.9 b	0.53 b	1080 c
Macoun/B.9		7.8 c	47.6 b	555 d	29.9 a	43.4 b	99.9 b	8.9 b	0.79 a	759 d
Cultivar/stock significance		**	**	**	*	**	*	*	NS	**
	Unirrigated	7.7 b	44.0	810 b	26.7 b	38.9 b	123.3 b	6.4 b	0.46 b	1008 b
	Irrigated	9.1 a	46.1	952 a	27.9 ab	50.0 a	160.7 a	9.3 a	0.66 a	1306 a
	Fertigated	8.9 a	43.2	956 a	27.1 a	46.6 a	160.3 a	10.3 a	0.63 a	1285 a
Irrigation treatment significance		**	NS	**	*	**	*	**	*	**
Interaction significance		NS	NS	*	*	NS	NS	NS	NS	*

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \le 0.05$.
*, **, or NS indicates treatment had a significant effect at $P \le 0.05$ or $P \le 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Honeycrisp, in which fertigation increased total shoot length, but with Gala irrigation had the highest total shoot length and was significantly different from fertigation and the unirrigated control. With Jonagold and Macoun there were no significant differences in total shoot length between the treatments. A third interaction resulted when irrigation increased average shoot length with Gala but with Jonagold and Macoun the unirrigated control and the irrigation treatment increased the average shoot length compared with the fertigation treatment (Table 4). A fourth interaction resulted when fertigation increased total tree length relative to the control with Mutsu but with Gala, irrigation had the greatest total tree length followed by fertigation and the unirrigated control with all treatments being significantly different from each other. Fertigation and irrigation increased total tree length similarly and were significantly different from the unirrigated control treatment for Honeycrisp. With Jonagold and Macoun there were no significant differences among treatments.

In the fourth year (2012), the fertigation and irrigation treatments increased TCSA, total shoot length, average shoot length, pruning weight, and total tree length similarly, and significantly more than the unirrigated control (Table 5). Fertigation and irrigation increased leader length similarly; however, only the irrigation treatment was significantly greater than the control. With fertigation, the number of limbs pruned was higher and significantly different from the control.

Cumulative tree growth during the first 4 years of the experiment showed that the fertigation and irrigation treatments increased leader length, total shoot length, cumulative pruning weight, and average shoot length similarly, and significantly more than the unirrigated control treatment (Table 5). No significant interaction was found between cultivar and

Table 4. Effect of irrigation and fertigation on tree growth of five apple cultivars in the third year (2011) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	TCSA (cm^2)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Pruning wt (g)	Spurs pruned per tree	Limbs pruned per tree	Total tree length (cm)
Main effect means									
Mutsu/M.9T337		12.6 a[i]	33 c	1191 c	22.4 b	331 b	29.7 c	0.76 c	1851 c
Gala/M.9Pajam2		13.8 a	48.2 a	2148 a	26.8 a	823 a	96.8 a	1.78 a	3571 a
Honeycrisp/M.9Nic29		10.3 b	28.9 c	1585 b	23 a	371 b	53.9 b	0.98 bc	2674 b
Jonagold/B.9		10.9 b	39.7 b	1281 c	23.2 a	469 b	51.6 b	1.10 bc	2077 c
Macoun/B.9		9.7 b	39 b	856 d	22.1 a	362 b	52.4 b	1.05 ab	1410 d
Cultivar/stock significance		**	**	**	**	**	**	*	**
	Unirrigated	9.9 b	37.6 ab	1267 c	23.3 ab	349 b	45.2 b	0.96 b	2081 b
	Irrigated	12.1 a	39.2 a	1562 a	24.3 a	537 a	62.7 a	1.35 a	2519 a
	Fertigated	12.4 a	36.4 b	1418 b	22.9 b	528 a	62.5 a	1.38 a	2370 a
Irrigation treatment significance		**	*	**	*	**	**	**	**
Interaction significance		NS	*	*	*	NS	NS	NS	*

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \le 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \le 0.05$ or $P \le 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Table 5. Effect of irrigation and fertigation on tree growth of five apple cultivars in the fourth year (2012), cumulative (Cum.) growth over the first 4 years (2009–12), and trunk growth in the fifth year (2013) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	TCSA 2012 (cm^2)	Leader growth 2012 (cm)	Total shoot growth 2012 (cm)	Avg shoot length 2012 (cm)	Pruning wt 2012 (g)	Limbs pruned per tree 2012	Total tree length 2012 (cm)	Cum. 2009–12 leader growth (cm)	Cum. 2009–12 total shoot growth (cm)	Cum. 2009–12 pruning wt (g)	Avg shoot length 2009–12 (cm)	TCSA 2013 (cm^2)	TCSA increase 2013 (cm^2)
Main effect means														
Mutsu/M.9T337		15.8 a[i]	34.6 ab	2355 bc	23.9 a	736 b	2.5 b	3546 b	143 c[i]	4454 b	1180 bc	22.6 b	19.6 a[i]	3.8 a
Gala/M.9Pajam2		15.7 a	36.7 a	4050 a	25.6 a	1111 a	3.4 a	6198 a	182 a	8092 a	2256 a	26.3 a	19.3 a	3.6 a
Honeycrisp/M.9Nic29		11.5 bc	27.4 c	1875 cd	20.8 b	520 c	2.2 bc	3460 b	123 d	4805 b	984 c	19.5 c	14.5 b	3.0 b
Jonagold/B.9		12.6 b	33.3 b	2382 b	24.0 a	647 b	2.2 bc	3662 b	159 b	4727 b	1266 b	25.5 a	15.0 b	2.4 c
Macoun/B.9		11.0 c	24.9 c	1415 d	18.6 c	486 c	1.9 c	2270 c	153 bc	3030 c	949.5 c	22.9 b	13.4 b	2.3 c
Cultivar/stock significance		**	**	**	**	**	**	**	**	**	**	**	**	**
	Unirrigated	11.6 b	28.6 b	1956 b	21.0 b	554 b	2.1 b	3224 b	142 b	4223 b	1030 b	21.5 b	14.1 b	2.5 b
	Irrigated	14.0 a	33.2 a	2733 a	23.7 a	771 a	2.5 ab	4295 a	156 a	5580 a	1479 a	24.3 a	17.2 a	3.2 a
	Fertigated	14.4 a	32.4 ab	2570 a	23.1 a	776 a	2.7 a	3988 a	157 a	5294 a	1475 a	24.2 a	17.7 a	3.3 a
Irrigation treatment significance		**	*	**	**	**	*	**	**	**	**	**	**	**
Interaction significance		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \le 0.05$.

*, **, or NS indicate treatment had a significant effect at $P \le 0.05$ or $P \le 0.01$ levels, or had a nonsignificant effect, respectively.

TCSA = trunk cross-sectional area.

irrigation treatment for cumulative tree growth.

During the fifth year (2013), fertigation and irrigation increased TCSA similarly and significantly more than the unirrigated control (Table 5). There was a significant interaction in TCSA increase between cultivar and irrigation treatment. Fertigation increased TCSA more than the irrigation and unirrigated treatments with Mutsu, but with Gala and Honeycrisp the fertigation and irrigation treatments increased TCSA similarly and significantly more than the control. There were no significant differences in TCSA increase among treatments for Jonagold and Macoun.

Leaf nutrient concentrations. In the first year (2009), the unirrigated control treatment had the highest N, Mg, S, and Zn, concentrations in the leaves being significantly greater than the irrigation and fertigation treatments (Table 6). However, the unirrigated control treatment had the lowest concentration of P followed by the fertigation and then the irrigation treatment. K and B concentrations were lower in the control treatment compared with the fertigation and irrigation treatments, which had similar concentrations. The fertigation treatment and the unirrigated control treatment had the highest concentration of Ca, but only the control was significantly higher than the irrigation treatment. The control treatment had the highest concentration of Mn follow by the irrigation then the fertigation treatment. There were no differences among treatments for Fe, Cu, and Al concentrations. In 2009 there were some interactions between cultivar and irrigation treatment for N, Ca, and Cu. With Mutsu, Gala, and Honeycrisp, the unirrigated treatment had significantly higher N concentrations than the irrigation or fertigation treatments; however, with Jonagold and Macoun, there were no significance differences among treatments. For Ca, the unirrigated control had a higher concentration than the irrigation or fertigation treatments, which were similar with Mutsu and Gala. However, with Honeycrisp the unirrigated control had the highest concentration, whereas the irrigation treatment had significantly higher Ca than the fertigation treatment. With Macoun, the fertigation treatment had the highest Ca concentration, which

Table 6. Effect of irrigation and fertigation on leaf nutrient concentration of five apple cultivars during the first year (2009) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	Al (ppm)
Main effect means													
Mutsu/M.9T337		2.85 a[i]	0.159 d	2.07 a	1.22 c	0.33 a	0.2 bc	21.6 c	53.8 ab	68.8 a	5.71 c	27.9 c	35.6 b
Gala/M.9Pajam2		2.71 bc	0.172 c	2.04 a	1.20 c	0.31 ab	0.2 bc	27.6 b	47.3 bc	64.9 a	6.41 b	30.4 b	43.7 a
Honeycrisp/M.9Nic29		2.79 ab	0.176 bc	1.67 c	1.35 b	0.28 bc	0.2 a	28.2 ab	51.7 ab	63.2 a	8.18 a	33.8 a	39.5 ab
Jonagold/B.9		2.63 c	0.186 a	1.67 c	1.48 a	0.28 bc	0.2 c	29.9 a	34.9 c	56.9 a	5.71 c	27.7 c	38.0 ab
Macoun/B.9		2.76 ab	0.18 ab	1.78 b	1.25 c	0.26 c	0.2 ab	21.0 c	65.8 a	60.3 a	5.70 c	22.1 d	33.6 b
Cultivar/stock significance		**	**	**	**	*	*	**	*	NS	**	**	NS
	Unirrigated	2.85 a	0.152 c	1.74 b	1.36 a	0.35 a	0.2 a	28.1 a	68.9 a	63.1 a	6.37 a	27.6 b	38.2 a
	Irrigated	2.71 b	0.188 a	1.93 a	1.26 b	0.26 b	0.2 b	24.2 b	47.8 b	64.4 a	6.32 a	28.7 a	37.2 a
	Fertigated	2.69 b	0.183 b	1.87 a	1.29 ab	0.26 b	0.2 b	24.8 b	35.1 c	61.0 a	6.36 a	29.0 a	38.8 a
Irrigation treatment significance		**	**	**	*	**	*	*	**	NS	NS	**	NS
Interaction significance		*	NS	NS	**	NS	NS	NS	NS	NS	*	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.

*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.

Table 7. Effect of irrigation and fertigation on leaf nutrient concentration of five apple cultivars in the second year (2010) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	Al (ppm)
Main effect means													
Mutsu/M.9T337		3.14 a[i]	0.170 bc	1.54 b	2.43 bc	0.43 ab	0.2 a	190.1 b	62.9 a	76.2 a	7.88 b	42.4 a	14.8 c
Gala/M.9Pajam2		2.79 b	0.160 c	1.60 b	1.79 d	0.40 b	0.2 c	145.6 c	54.5 a	71.1 ab	8.00 ab	39.1 bc	28.1 a
Honeycrisp/M.9Nic29		2.79 b	0.169 bc	1.28 c	2.52 ab	0.30 c	0.2 ab	228.9 a	57.3 a	75.2 a	7.15 c	41.1 ab	27.8 a
Jonagold/B.9		2.88 b	0.174 b	1.81 a	2.19 c	0.46 a	0.2 bc	142.6 c	59.1 a	67.6 b	8.59 a	42.1 a	25.1 ab
Macoun/B.9		2.81 b	0.187 a	1.82 a	2.74 a	0.31 c	0.3 a	160.3 c	60.2 a	73.4 ab	8.44 ab	37.9 c	18.7 bc
Cultivar/stock significance		**	*	**	**	**	**	**	NS	*	**	**	*
	Unirrigated	2.92 a	0.171 a	1.57 a	2.42 a	0.4 a	0.2 a	174.2 a	65.8 a	72.7 a	7.99 ab	40.2 a	25.1 a
	Irrigated	2.85 a	0.171 a	1.59 a	2.25 a	0.38 a	0.2 a	175.4 a	55.2 b	71.4 a	8.29 a	41.2 a	21.5 a
	Fertigated	2.87 a	0.173 a	1.66 a	2.32 a	0.37 a	0.2 a	171.6 a	55.3 b	74.0 a	7.74 b	40.3 a	22.4 a
Irrigation treatment significance		NS	NS	NS	NS	NS	NS	NS	*	NS	*	NS	NS
Interaction significance		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.

*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.

Table 8. Effect of irrigation and fertigation on flowering and fruiting of five apple cultivars in the second year (2010) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Blossom cluster no. per tree	Fruit no. per tree	Fruit wt (kg)	Yield (t/ha)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency (kg/cm^2 TCSA)	Fruit size (g)	Percent fruit drop (%)
Main effect means									
Mutsu/M.9T337		58.5 c[i]	20.6 b	7.09 a	20.25 a	2.35 c	0.815 a	362 a	30.3 a
Gala/M.9Pajam2		101.8 a	23.7 a	4.59 c	13.13 c	2.29 c	0.442 b	194 d	5.5 d
Honeycrisp/M.9Nic29		100.9 a	21.0 b	6.29 b	17.97 b	2.67 b	0.800 a	301 b	14.9 c
Jonagold/B.9		77.3 b	25.1 a	6.36 b	18.18 b	3.18 a	0.807 a	256 c	9.8 d
Macoun/B.9		53.4 c	17.1 c	3.06 d	8.75 d	2.21 c	0.398 b	181 e	20.2 b
Cultivar/stock significance		**	**	**	**	**	**	**	**
	Unirrigated	68.2 c	17.2 b	4.50 b	12.86 b	2.25 b	0.594 b	272 a	18.3 a
	Irrigated	87.9 b	24.4 a	6.02 a	17.20 a	2.73 a	0.678 a	248 b	15.4 b
	Fertigated	79.7 a	23.1 a	5.97 a	17.07 a	2.65 a	0.694 a	259 c	14.6 b
Irrigation treatment significance		**	**	**	**	**	**	**	**
Interaction significance		NS	NS	NS	NS	**	*	**	**

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.

was significantly different from the unirrigated control.

During the second year (2010), there were no significant differences between the treatments in nutrient concentrations in the leaves for N, P, K, Ca, Mg, S, Zn, Fe, B, and Al (Table 7); however, the unirrigated treatment had the highest concentration of Mn compared with the irrigation and the fertigation treatments. For Cu, the irrigation treatment had the highest concentration compared with the fertigation treatment. In 2010 there were no significant interactions between cultivar and irrigation treatment.

Flowering and yield. In the second year (2010), the fertigation treatment had the highest blossom cluster number per tree followed by the irrigation treatment, and then the unirrigated control had the lowest number (Table 8). The fertigation and irrigation treatments had the highest fruit number, fruit weight, yield, crop load, and yield efficiency compared with the control (Fig. 1); however, the control treatment had the largest fruit size and the fertigation treatment had the smallest fruit size. The percent fruit drop was higher with the unirrigated control treatment compared with the irrigation and fertigation treatments, which were not different from each other. Among cultivars, Gala and Honeycrisp had many more blossom clusters than the other cultivars. There was a significant interaction between cultivar and irrigation treatment for crop load, yield efficiency, fruit size, and fruit drop. Fertigation and irrigation had similar crop loads and yield efficiencies, which were significantly higher than the control with Mutsu, Honeycrisp, and Jonagold but with Gala and Macoun there were no differences among irrigation treatments. The control treatment had the highest percent fruit drop compared with the irrigation and fertigation treatments with Mutsu but with Gala, Honeycrisp, and Jonagold there were no differences in fruit drop between the treatments. With Macoun the fertigation and irrigation treatments had the highest fruit drop compared with the control but only fertigation was significantly different from the control.

In the third year (2011), crop load and yield efficiency were highest with the unirrigated control treatment compared with the fertigation and irrigation treatments (Table 9). Despite the few differences among the treatments in the third year, there were various significant interactions of cultivar and treatment. With Mutsu, the unirrigated control and the irrigation treatment had higher fruit number, fruit weight, yield, crop load, yield efficiency, and fruit size than the fertigated treatment. However, there were no statistical differences among treatments with Gala with any of the variables (Fig. 1). With Honeycrisp, the unirrigated control and the irrigation treatment had similar fruit weight, yield, crop load, and fruit size; however, only the control was significantly greater

Fig. 1. Yield of fertigated Gala/M.9 apple trees in the second year (2010) (A), third year (2011) (B), fourth year (2012) (C), and fifth year (2013) (D) at Geneva, NY, USA.

Table 9. Effect of irrigation and fertigation on fruiting of five apple cultivars in the third year (2011) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Fruit no. per tree	Fruit wt (kg)	Yield (t/ha)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency (kg/cm^2 TCSA)	Fruit size (g)	Percent fruit drop (%)
Main effect means								
Mutsu/M.9T337		33.7 b[i]	9.47 a	27.1 a	2.96 cd	0.82 a	299 a	14.4 a
Gala/M.9Pajam2		64.4 a	9.60 a	27.4 a	4.78 a	0.71 abc	151 d	5.3 b
Honeycrisp/M.9Nic29		22.8 c	6.08 b	17.4 b	2.40 d	0.64 bc	276 b	17.2 a
Jonagold/B.9		39.7 b	8.36 a	23.9 a	3.82 bc	0.80 ab	231 c	6.6 b
Macoun/B.9		36.9 b	5.88 b	16.8 b	3.87 b	0.62 c	161 d	18.6 a
Cultivar/stock significance		**	**	**	**	*	**	**
	Unirrigated	40.9	8.15	23.3	4.16 a	0.84 a	220	11.7
	Irrigated	40.0	8.14	23.3	3.41 b	0.70 b	223	12.0
	Fertigated	37.5	7.38	21.1	3.12 b	0.61 b	228	13.2
Irrigation treatment significance		NS	NS	NS	**	**	NS	NS
Interaction significance		**	**	**	*	*	**	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

than the fertigation treatment. With Jonagold, the control had the highest fruit number, fruit weight, yield, crop load, and yield efficiency compared with the fertigation and irrigation treatments. With Macoun, the fertigation and irrigation treatments had the highest fruit number, fruit weight, and yield, but only the irrigation treatment was significantly different from the control.

In the fourth year (2012), the fertigation and the irrigation treatments had the highest blossom cluster number, fruit weight, yield, and fruit size compared with the unirrigated control treatment (Table 10). The fertigation and irrigation treatments also had the highest fruit number; however, only the fertigation treatment was significantly different from the control (Fig. 1). Crop load was greatest with the control and fertigation treatments but only the unirrigated control was significantly different from than the irrigation treatment. This year there were no significance interactions between cultivar and treatment.

During the last year of the experiment (2013), irrigation and the unirrigated control treatment had the highest fruit number, whereas the fertigation treatment was significantly lower than irrigation treatment but similar to the control (Table 11). Fruit weight and yield with the irrigation treatment were statistically greater than with the fertigation and the control treatments (Fig. 1). The unirrigated control treatment had the highest crop load, followed by the irrigation treatment and lastly by the fertigation treatment. Yield efficiency was highest with the control and irrigation treatments, which were significantly greater than the fertigation treatment. Irrigation and fertigation had the highest fruit size; however, they also had the highest percent fruit drop, compared with the control. However, there was a significant interaction between cultivar and treatment with percent fruit drop, in which Mutsu, Gala, Jonagold, and Macoun did not have differences in drop between the treatments.

Table 10. Effect of irrigation and fertigation on flowering and fruiting of five apple cultivars in the fourth year (2012) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Blossom no. per tree	Fruit no. per tree	Fruit wt (kg)	Yield (t/ha)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency (kg/cm^2 TCSA)	Fruit size (g)	Percent fruit drop (%)
Main effect means									
Mutsu/M.9T337		162 c[i]	32.2 d	8.3 d	23.7 d	2.08 c	0.53 c	261 a	14.2 ab
Gala/M.9Pajam2		343 a	126.9 a	18.1 a	51.6 a	8.26 a	1.17 b	144 d	2.9 d
Honeycrisp/M.9Nic29		239 b	90.9 b	17.1 ab	48.8 ab	7.89 a	1.48 a	190 c	11.2 bc
Jonagold/B.9		225 b	69.2 c	14.3 bc	40.8 bc	5.73 b	1.16 b	211 b	7.9 c
Macoun/B.9		183 c	78.5 bc	11.0 cd	31.4 cd	7.40 a	1.03 b	141 d	15.2 a
Cultivar/stock significance		**	**	**	**	**	**	**	**
	Unirrigated	209 b	75.3 b	12.1 b	34.6 b	6.72 a	1.08	181 b	10.8
	Irrigated	236 a	79.1 ab	14.5 a	41.3 a	5.84 b	1.07	197 a	9.5
	Fertigated	248 a	84.2 a	14.8 a	42.2 a	6.25 ab	1.08	192 a	10.5
Irrigation treatment significance		**	*	**	**	*	NS	**	NS
Interaction significance		NS	NS	NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Table 11. Effect of irrigation and fertigation on fruiting of five apple cultivars in the fifth year (2013) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Fruit no. per tree	Fruit wt (kg/tree)	Yield (t/ha)	Crop load (fruit no./ cm² TCSA)	Yield efficiency (kg/cm² TCSA)	Fruit size (g)	Percent fruit drop (%)
Main effect means								
Mutsu/M.9T337		130.1 b	32.95 a	94.2 a	6.90 ab	1.72 a	253 a	6.27 b
Gala/M.9Pajam2		140.4 a	23.07 b	65.9 b	7.52 a	1.23 c	165 c	3.16 c
Honeycrisp/M.9Nic29		43.1 d	8.79 d	25.1 d	3.39 d	0.68 e	223 b	19.33 a
Jonagold/B.9		87.6 c	21.35 b	61.0 b	5.95 c	1.44 b	247 a	4.66 bc
Macoun/B.9		79.9 c	12.30 c	35.1 c	6.19 bc	0.95 d	155 d	17.70 a
Cultivar/stock significance		**	**	**	**	**	**	**
	Unirrigated	96.9 ab	18.90 b	54.0 b	6.88 a	1.33 a	200 b	8.87 b
	Irrigated	101.8 a	21.10 a	60.3 a	5.94 b	1.22 a	212 a	10.67 a
	Fertigated	89.7 b	19.12 b	54.6 b	5.13 c	1.07 b	215 a	11.00 a
Irrigation treatment significance		*	*	*	**	**	**	**
Interaction significance		NS	NS	NS	NS	NS	NS	**

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Nevertheless, with Honeycrisp, the irrigation and the fertigation treatments had more fruit drop compared with the control treatment.

The irrigation and fertigation treatments had the highest cumulative yield per tree, and yield per hectare compared with the unirrigated control (Table 12). Yield efficiency was highest for the control treatment followed by the irrigation treatment and lastly the fertigation treatment. Average crop load was very similar for the irrigation and fertigation treatments but lower than the control treatment. Fruit size was largest in the irrigated treatment, intermediate in the fertigated treatment, and smallest in the unirrigated treatment.

Fruit quality, storage disorders, and packout. Fruit quality was evaluated only during the third and fourth growing seasons (2011 and 2012). In 2011, the fertigation and the unirrigated control treatments had the highest dry matter concentration in the fruit, but only the fertigation treatment was significantly different from the irrigation treatment (Table 13). Irrigation showed the highest bitter pit incidence, which was significantly different from the fertigation and unirrigated treatments. There was a significant interaction between cultivar and irrigation treatment for bitter pit. With Mutsu, Jonagold, and Macoun there were no differences in bitter pit incidence between treatments. However, for Honeycrisp the irrigation treatment had the highest incidence followed by the fertigation treatment, whereas the unirrigated control had the lowest incidence. With Gala, the unirrigated control treatment had significantly higher incidence of bitter pit compared with the irrigation and fertigation treatments.

During the fourth growing season (2012), the unirrigated control treatment had significantly higher dry matter concentration than the irrigation and fertigation treatments (Table 14). The rest of the fruit quality variables did not show any significant differences among the irrigation treatments. Bitter pit incidence with Honeycrisp was very low in the fourth year (2.5%) compared with the third year, which had 16.8%. There

Table 12. Effect of irrigation and fertigation on cumulative fruiting of five apple cultivars over 5 years (2009–13) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Cumulative yield (kg/tree)	Cumulative yield (t/ha)	Cumulative yield efficiency (kg/cm² TCSA)	Avg crop load (fruit no./ cm² TCSA)	Avg fruit size (g)
Main effect means						
Mutsu/M.9T337		57.8 a[i]	165 a	3.05 b	3.6 d	293.8 a
Gala/M.9Pajam2		55.3 a	158 a	2.95 bc	5.7 a	163.4 d
Honeycrisp/M.9Nic29		38.3 c	109 c	2.77 c	4.1 c	247.3 b
Jonagold/B.9		50.0 b	143 b	3.41 a	4.7 b	236.0 c
Macoun/B.9		32.2 d	92 d	2.50 d	4.9 b	159.5 d
Cultivar/stock significance		**	**	**	**	**
	Unirrigated	43.7 b	125 b	3.14 a	5.0 a	218.1 b
	Irrigated	49.7 a	142 a	2.94 b	4.5 b	222.8 a
	Fertigated	47.1 a	135 a	2.74 c	4.3 b	220.8 ab
Irrigation treatment significance		**	**	**	**	*
Interaction significance		NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.
*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.
TCSA = trunk cross-sectional area.

Table 13. Effect of irrigation and fertigation on fruit quality and storage disorders of five apple cultivars in the third year (2011) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Fruit firmness (N)	Soluble solids (%)	Dry matter (%)	Storage disorders incidence (%)		
					Senescent breakdown	Bitter pit	Watercore
Main effect means							
Mutsu/M.9T337		59.2 c[i]	14.5 a	15.1	0.0	0 b	0.0 b
Gala/M.9Pajam2		67.6 a	14.4 a	14.3	0.0	0.8 b	0.0 b
Honeycrisp/M.9Nic29		62.3 b	13.4 b	13.9	0.0	16.8 a	0.0 b
Jonagold/B.9		46.3 d	13.6 b	14.1	2.1	0.0 b	0.0 b
Macoun/B.9		46.7 d	12.8 c	13.2	0.0	0.0 b	3.9 a
Cultivar/stock significance		**	**	NS	NS	**	*
	Unirrigated	53.4	13.8	14.4 ab	0.0	1.6 b	0.0
	Irrigated	53.4	13.6	13.4 b	1.0	5.7 a	1.1
	Fertigated	53.4	13.9	14.6 a	0.0	2.7 b	1.2
Irrigation treatment significance		NS	NS	*	NS	*	NS
Interaction significance		NS	NS	NS	NS	**	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test $P \leq 0.05$.

*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.

was a significant interaction of cultivar and irrigation treatment for superficial scald. With Mutsu, Jonagold, and Macoun, no superficial scald was found; however, with Gala the unirrigated control and the irrigation treatment had increased incidence of superficial scald compared with the fertigation treatment. With Honeycrisp, the fertigation treatment and the unirrigated control had significantly higher incidence than the irrigation treatment.

In the fourth year (2012), we also evaluated fruit packout, which did not differ significantly due to irrigation treatment, nor was there was a significant interaction between cultivar and irrigation treatments (data not shown). Among cultivars, Gala and Jonagold had high packout (~70% XF), whereas Honeycrisp and Macoun had low packout (~30% XF). Mutsu was intermediate.

A calculation of the economic benefit of having irrigation in Tall Spindle orchards showed that for all cultivars there was a positive economic benefit in cumulative crop value from irrigation or fertigation (Table 15). The increase in crop value was greatest for Mutsu followed by Gala and then Honeycrisp. The benefit to Macoun and Jonagold was much less but still positive.

Discussion

Vegetative growth. Our results show that that early apple tree growth in a humid climate is improved by irrigation in the first few years even when both the irrigated and unirrigated treatments had high nitrogen fertilization. These results are similar to those obtained by Robinson and Stiles (2004) in a humid climate with 'Redchief Delicious', Mutsu, and 'Empire' apple trees. This also agrees with the results of Neilsen et al. (1997) in a dry climate. In the present study, fertigation also improved tree growth similarly to the irrigation treatment; however, it is important to emphasize that in both the irrigated and fertigation treatments, the N fertilizer input was the same in both treatments. Interestingly, the N concentration in the leaves in the unirrigated treatment in the first year was the highest of the three irrigation treatments. We expected the fertigation treatment to have the highest N concentration. An explanation may be that because there was less shoot growth in the unirrigated control, the nutrients were more concentrated than in the irrigation or fertigation treatments in which the nutrients were more diluted there due to greater shoot growth.

The similar effect of fertigation and irrigation treatments on growth indicates that the way that N fertilizer was applied was not important. For the irrigation treatment, N was applied to the soil manually per tree, and the irrigation water likely moved the fertilizer into the soil profile for root uptake. With fertigation, the fertilizer was dissolved in the irrigation water. In both cases it appears that the added water moved the N very similarly into the soil profile. In contrast, the unirrigated treatment also received the same amount of dry fertilizer added to the soil surface, but rainwater alone did not result in similar growth as the irrigated treatment. Hipps (1992) showed that increasing the rate of broadcast application of nitrogen from 68 to 189 $kg \cdot ha^{-1}$ had no effect on tree growth or yield of apples; however, others have shown that additional growth can be achieved with the use of fertigation (Kipp 1992; Neilsen et al. 1999). They argued that growth was improved because the nutrients were delivered more precisely to the root system than when broadcasted. In our case where the irrigation treatment improved tree growth very similarly to the fertigation treatment, it appears that the nitrogen likely was delivered precisely in both cases.

The increase in pruning weights with the irrigation treatments in our study was also observed by Reynolds et al. (2005). The increase in pruning weights indicates that pruning labor costs would be higher under the irrigation or fertigation treatments.

Flowering and fruiting. The irrigation and fertigation treatments in our study had significantly higher cumulative yields over the 5 years than the unirrigated control. For all the cultivars tested in this trial, the fertigation and irrigation treatments behaved very similarly in terms of yield. This indicates that the use of drip irrigation in humid climates aids in the utilization and movement of the applied fertilizer, whether the fertilizer is soil applied or dissolved in the irrigation water (fertigation). These results are similar to those obtained by Robinson and Stiles (2004) on 'Redchief', Mutsu, and 'Empire'. Our results are also supported by

Table 14. Effect of irrigation and fertigation on fruit quality and storage disorders of five apple cultivars in the fourth year (2012) at Geneva, NY, USA.

Cultivar/stock	Irrigation treatment	Fruit firmness (N)	Soluble solids (%)	Dry matter (%)	Storage disorders incidence (%)					
					Superficial scald	Bitter pit	Lenticel breakdown	Senescent breakdown	Flesh browning	Watercore
Main effect means										
Mutsu/M.9T337		61.8 b[i]	17.8 a	20.9 a	0.0 b	0.0 b	0 b	12.8 a	0 b	0.0
Gala/M.9Pajam2		64.1 a	16.5 b	19.7 b	0.5 b	0.5 b	0.2 b	0.0 c	3.9 a	0.2
Honeycrisp/M.9Nic29		53.8 c	14.1 e	17.0 d	4.8 a	2.5 a	3.1 a	0.0 c	0 b	0.0
Jonagold/B.9		46.3 e	16.0 c	19.0 bc	0.3 b	0.0 b	0.4 b	8.0 b	0 b	0.0
Macoun/B.9		49.8 d	15.1 d	18.2 c	0.0 b	0.3 b	0 b	3.6 bc	0.3 b	0.5
Cultivar/stock significance		*	**	**	**	*	**	**	**	NS
	Unirrigated	55.2	16.0	19.4 a	1.5	0.7	0.7	5.0	1.3	0.1
	Irrigated	54.7	16.1	18.7 b	0.5	0.8	0.6	5.1	0.7	0.2
	Fertigated	55.6	15.7	18.7 b	1.4	0.5	1.0	4.6	0.5	0.1
Irrigation treatment significance		NS	NS	*	NS	NS	NS	NS	NS	NS
Interaction significance		NS	NS	NS	*	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.

*, **, or NS indicate treatment had a significant effect at $P \leq 0.05$ or $P \leq 0.01$ levels, or had a nonsignificant effect, respectively.

other studies in which fertigation did not enhance flowering or increase productivity in fertile soils more than irrigation (Dencker and Hansen 1990; Hipps 1992; Ramirez and Hoad 1981). In contrast, a study done in Hungary by Bubán and Lakatos (2000) showed that with two different forms of nitrogen (ammonium and calcium nitrate), flowering and yield were affected much more by the method of nitrogen application rather than the form of N. The use of fertigation resulted in higher cropping and flowering than the conventional standard treatment with the two different types of nitrogen fertilizers.

We found no effect of irrigation or fertigation treatments on fruit quality. These results are in contradiction to the results of Porro et al. (2013) who found that fertigation significantly improved fruit quality, with higher soluble solids concentration and firmer fruit than the granular application. During the 2011 season, bitter pit incidence was higher with irrigation and fertigation for Honeycrisp, than the unirrigated treatment. This result can be explained by the negative effects of nitrogen fertilization on bitter pit incidence, which usually occur under excessive supply conditions (Neilsen and Neilsen 2009). However, in our trial, fruit packout was not improved by the use of irrigation or fertigation compared with the unirrigated treatment.

From a practical perspective, both irrigation and fertigation increased gross crop value of each of the five scion/rootstock combinations we tested when planted in a high-density Tall Spindle orchard. Given the variation in growth habits of the scion cultivars and the range of effects of the rootstocks used, fertigation or irrigation practices are likely to benefit early establishment and cropping of many scion rootstock combinations.

Conclusions

The success of a high-density apple orchard depends on growing the trees to fill the allotted space as quickly as possible while at the same time getting the trees into full production as fast as possible so that the high investment can be recovered as soon as possible. However, many orchards experience inadequate tree growth in the early life of the planting, therefore affecting both early and mature cropping. This study

Table 15. The effect of irrigation on cumulative crop value over the first 5 years of a Tall Spindle planting of five apple cultivars at Geneva, NY, USA (2009–13).

Cultivar/stock	Irrigation treatment	Cumulative yield (t/ha)	Cumulative crop value ($/ha)	Difference between best treatment and unirrigated control ($/ha)
Mutsu/M.9T337	Unirrigated	144	$93,795[i]	
	Irrigated	179	$116,610	$22,815
	Fertigated	171	$111,085	
Gala/M.9Pajam2	Unirrigated	146	$94,900	
	Irrigated	170	$110,630	$15,730
	Fertigated	159	$103,155	
Honeycrisp/M.9Nic29	Unirrigated	107	$138,710	
	Irrigated	116	$151,320	$12,610
	Fertigated	105	$136,240	
Jonagold/B.9	Unirrigated	141	$91,455	
	Irrigated	144	$93,730	$2,275
	Fertigated	144	$93,340	
Macoun/B.9	Unirrigated	85	$55,250	
	Irrigated	99	$64,155	$8,905
	Fertigated	93	$60,190	

[i] The economic analysis used fruit prices of $0.65/kg for Mutsu, Gala, Jonagold, and Macoun and the fruit price for Honeycrisp was $1.3/kg.

was intended to provide a solution to problems of poor tree growth through irrigation or fertigation.

Our results showed that the use of irrigation in humid climates is beneficial for tree growth and productivity in the early life of the planting. Growers should not rely solely on rain because in some years it is sporadic and will not provide sufficient water. Fertigation can provide a more precise method of delivering nutrients and water, especially in the first year of growth when the root system is small and has not been established but was not better than irrigation alone. Both irrigation and fertigation resulted in larger trees with greater mature bearing capacity. These results are especially important with highly feathered trees, in which the water stress can be more pronounced due the extensive early leaf area and a limited root system after the nursery digging operation. This type of tree is the one with the highest yield potential in the first 5 years if managed under irrigation. The adoption of irrigation or fertigation in new high-density orchards by New York State apple growers will improve their profitability.

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