

Growth and Yield Responses to Mulches and Cover Crops under Low Potassium Conditions in Drip-irrigated Apple Orchards on Coarse Soils

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Abstract. Fertigated ‘Gala’ apple trees on M.9 (*Malus domestica* Borkh.) rootstock, planted in 1998, were grown on a coarse soil for 6 years (1998 to 2003) and exposed to eight orchard floor vegetation management treatments within the tree row. These consisted of a glyphosate control; three waste paper mulch treatments [spray-on mulch paper mulch (SM), SM incorporated with dichlobenil, SM applied over uniformly spread shredded office paper (SOP)]; and four living cover crop mulch treatments [dwarf white clover (WC), sweet clover (SC), hairy vetch (HV), and annual rye]. There were no significant treatment effects on leaf nitrogen (N) and phosphorus (P) status; however, leaf potassium (K) levels were negatively affected by the living mulch treatments in 2 of 5 years. Tree vigor was diminished by several of the orchard floor vegetation management systems in 5 of 6 years. Trees receiving an SM treatment grew more rapidly than trees receiving the ground cover treatments and trees receiving a glyphosate treatment had relatively poor but comparable growth to several of the cover crop treatments. Growth response in trees receiving SM were observed in all production years. After 6 years, cumulative yields were highest from trees receiving any of the three SM or glyphosate treatments and significantly less for any of the ground cover treatments. Weed growth within the rye cover crop was significantly reduced in comparison with the other living mulches; however, it remained sufficiently competitive to contribute to diminished overall yield and tree growth in comparison with the SM and glyphosate control treatments. Overall, response of leaf K concentration to mulch treatments was insufficient to prevent low K levels after 5 years. The addition of K through the organic mulches or recycling of K by cover crops was insufficient to avoid the development of low leaf K levels. Annual fertigation of K, in addition to N and P, appears necessary to maintain adequate vigor and yield when using mulches or cover crops in intensive, drip-irrigated apple orchards grown on coarse soils.

The development and consequences of K deficiency in intensively managed apple orchards grown on coarse-textured soils under drip irrigation have been identified previously (Cummings, 1985; Neilsen et al., 1998). Correction of K deficiency through the use of mulches has been previously demonstrated on apple (Reuther and Boyton, 1940; Wander and Gourley, 1943) and peach (Baker, 1949). This response is related in part to actual K contained in the mulch, increased exchangeable K in the

soil profile as a result of increased organic matter, and decreased K fixation resulting in greater penetration into the root zone (Wander and Gourley, 1945).

Many of the orchard soils in the major fruit production regions of the Pacific Northwest of North America (PNW) are coarse-textured sandy loams to sand characterized by inherently low organic matter contents and low cation exchange capacity (CEC) (Wittneben, 1986). Like with many soils in western North America, soils of the Okanagan region have high to very high available K (Mehlich-3), averaging 364 mg K/kg with a cv of 15% in a recent soil survey of ≈500 samples collected from agricultural fields throughout the region (Kowalenko et al., 2009). Nevertheless, K deficiency has rapidly developed in high-density apple orchards on coarse-textured soils

in the Okanagan after the addition of NH₄-N fertilizers through drip irrigation systems (fertigation) despite initially adequate soil K levels over the whole orchard (Neilsen et al., 1994) or between the tree rows (Neilsen et al., 2000). In addition, the requirement for effective weed control within intensively grown orchards using dwarfing rootstocks, especially on coarse soils (Hogue and Neilsen, 1987; Merwin, 2003), and the potential benefits of organic mulches in mitigating soil management and K deficiency problems commonly observed in these regions (Neilsen et al., 1998) is of interest.

The trend to reduce or completely eliminate pesticides, including herbicides, has led to greater research efforts toward alternative methods of pest and weed control. Several organic materials are of particular interest for use as mulches in orchards in the PNW. Recycled waste paper, available in large quantities locally, as shredded office paper, has been advocated for use in conventional agricultural production systems (Edwards, 1997). Shredded office paper is permeable to water and can temporarily be an effective barrier to weeds. In addition to weed control, organic mulches offer several advantages over the exclusive use of herbicides. Mulches provide improved soil moisture conservation and can moderate soil temperatures (Neilsen et al., 1986). As a source of carbon and mineral nutrients, they can improve soil structure, increase CEC, soil biological activity, and available soil N (Forge et al., 2008; Hogue and Neilsen, 1987; Koehn et al., 2000; Merwin et al., 1995; Neilsen et al., 2003a). Performance of trees in low-fertility soils can improve after organic amendment application (Neilsen et al., 2003b).

Disadvantages of mulches include limited availability of satisfactory materials, inconsistent composition, cost of shipping, and difficulty of application, which can affect adoption by growers. Strategies to overcome these challenges have led to the development of sprayed-on mulch technologies and the use of in-row cover crops (Hogue et al., 2003). Cover cropping, like mulching, is a well-established practice, but in recent years, new species of plants with allelopathic and biofumigant properties have been introduced (Barnes and Putnam, 1983; Reberg-Horton et al., 2005). Ground covers, sometimes referred to as “living mulches,” have become popular in organic orchards in particular (Hartwig and Ammon, 2002). However, finding plant species that can outcompete weeds without reducing crop vigor have been elusive because many have been associated with reduced tree growth and yields (Schenk and Wertheim, 1992).

The objective of this study was to determine the effect of various organic mulches and cover crops, grown under low K conditions, on nutrient uptake, growth, and yield of a high-density apple orchard.

Materials and Methods

A 6-year experiment was initiated at the Pacific Agri-food Research Center, Summerland, British Columbia (long. 49°33'59" N, lat. 119°38'12" W) in 1998 using ‘Gala’ (cv.

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Imperial apple (*Malus domestica* Borkh.) on M.9 rootstock growing in a Skaha gravelly sandy loam, an Orthic Brown soil commonly planted to tree fruits and vineyards in the south Okanagan (Wittneben, 1986). These soils are coarse-textured, low in organic matter, have 25 cm A horizons, and weakly developed B horizons (S. Smith, personal communication). Furthermore, they have low CEC and basic pH ranging from 7 to 9 depending on the soil horizon. These soils are rapidly drained and low in water-holding capacity, necessitating frequent irrigation for adequate production. At the experimental site, Mehlich-1 extractable K concentrations were adequate for fruit production, averaging 162 mg·kg⁻¹ with a SD of 35 mg·kg⁻¹ (n = 36) before the establishment of the experiment, indicating moderate soil K status.

Trees were planted in the spring of 1998, spaced 1.0 m within and 3.0 m between rows (3333 trees/ha), trained to a slender spindle orchard system, and trickle-irrigated by drip emitters. Irrigation is required in the region and was applied daily from May to October each year to exceed minimum requirements through two 4-L·h⁻¹ drip emitters located 0.3 m, one on either side of the trunk, within the tree row, and above the mulch treatments. Fertilizers were applied annually through the irrigation system, beginning in 1998 with a total of 10 g P/tree as 10N–34P–0K (first year only) and 30g N as 34N–0P–0K at weekly intervals over an 8-week period beginning in mid-May annually, soon after full bloom. Fruit were thinned by hand ≈50 to 60 d after full bloom to maintain maximum final crop loads at harvest of 0.7, 3.3, 4.3, 4.0, and 6.3 fruit/cm² trunk cross-sectional area (TCA) in 1999 to 2003, respectively. Other pest and cultural management followed standard practices for the region (British Columbia Ministry of Agriculture and Food, 2007).

Eight treatments were applied in a randomized complete block design; each treatment plot contained four measurement trees and a “guard” tree between plots to minimize treatment interference. Treatments were replicated six times. Treatments were established in August (spray-on mulch treatments) and early September (cover crops) of 1998 and maintained over 10 m² (5 m from guard to guard in a 2.0-m wide strip centered on the tree rows). The treatments consisted of: 1) glyphosate control, a standard practice in commercial orchards involving maintenance of an in-row weed-free strip achieved through multiple annual applications of glyphosate (N-phosphonomethylglycine) at 1.0 kg a.i./ha as required (usually in early May, mid-June, late August, and late October); 2) SM applied uniformly to the plot surface and left unincorporated at 24 t·ha⁻¹ [dry weight (DW)]; 3) Treatment 2 incorporated with 10 kg·ha⁻¹ dichlobenil (Casoron 50 WP); 4) Treatment 2 applied over uniformly spread SOP at 5 t·ha⁻¹ (DW); 5) dwarf WC (*Trifolium repens* L. cv. Tahora) seeded at a rate of 40 kg·ha⁻¹; 6) winter rape (*Brassica napus* L. cv. Essex) seeded at a rate of 20 kg·ha⁻¹ (1998 only) followed by sweet clover (*Melilotus* L.) (1999 to 2003), henceforth referred to as a SC treatment. Winter rape

was difficult to establish and only sparsely covered the area beneath the tree, hence the reason for switching SC after 1998; 7) HV (*Vicia villosa* L.) and an oats (*Avena sativa* L.) nurse crop seeded at a rate of 180 kg·ha⁻¹ and 200 kg·ha⁻¹, respectively; and 8) annual rye (*Secale cereale* L. cv. Wheeler) seeded at a rate of 200 kg·ha⁻¹.

The sprayed-on mulch material was derived as a byproduct of the newsprint recycling industry (NewsTech Recycling, Coquitlam, British Columbia, Canada) containing ≈360 g·kg⁻¹ carbon (C), 3 g·kg⁻¹ N, 52 g·kg⁻¹ calcium (Ca), 120 mg·kg⁻¹ K, 241 mg·kg⁻¹ P, 703 mg·kg⁻¹ magnesium (Mg), 425 mg·kg⁻¹ iron (Fe), 40 mg·kg⁻¹ manganese (Mn), 77 mg·kg⁻¹ zinc (Zn), and 176 mg·kg⁻¹ copper (Cu) on a DW basis (Hogue et al., 2003). For ease of application and to simulate potential commercial application, a slurry was made by mixing 12 kg newsprint fiber (DW), 3 kg wood fiber (softwood coarse sawdust), and 200 g tackifier “organic glue” (Quality Seeds, Formerly Dawson Seeds, Langley, British Columbia, Canada) in 100 L water of product and spraying the mixture through a specialized tractor-mounted research sprayer. Two sprays were made at each application date to obtain the required rate of 24 t·ha⁻¹ newsprint fiber. After application, the material formed a hard crust on the surface that acted as a barrier to weed germination and growth. However, cracks subsequently formed with orchard traffic and exposure to rain and irrigation. Any weeds that germinated were permitted to grow until spot treatment with glyphosate in accordance with the application schedule indicated in Treatment 1. Applications were made 19 Aug. 1998 and repeated 27 June 2000 and 30 May 2002. The rationale for including SOP with SM in Treatment 4 was to produce a durable mulch to withstand cracking on the surface, thereby preventing weed germination and growth within these fissures. The nutrient concentration of the SOP material (DW basis) was ≈396 g·kg⁻¹ C, 33 g·kg⁻¹ N, 11 g·kg⁻¹ P, 5 g·kg⁻¹ K, 24 g·kg⁻¹ Ca, 2 g·kg⁻¹ Mg, 758 mg·kg⁻¹ Zn, 977 mg·kg⁻¹ Cu, and 235 mg·kg⁻¹ Mn (Nielsen et al., 2007).

All cover crops (Treatments 5 to 8) were reseeded in late August or early September each year. Except for the rye treatment, seeds were broadcast on the soil surface followed by light raking and periodically overhead-irrigated until established within the “weed-free” area within each row. The rye was seeded in furrows 15 cm apart and to a depth of 2 cm. In the spring of each year, just before bloom (early May), cover crops were trimmed using a gasoline-powered string “weed-eater” to a height of 2.5 to 7.5 cm and the residue spread evenly within the 2-m wide strip centered beneath the tree. To reduce competition and recycle organic matter and nutrients contained therein, all cover crop treatments received “spot” application of 1.0 kg glyphosate/ha shortly after bloom made selectively to weeds followed by two to three repeat applications at 4- to 6-week intervals before reseeding the cover crop in August of each year. Because of the highly competitive nature of the rye species, sprays

were directed within the entire plot area (2 m × 10 m), whereas for the WC, SC, and HV treatments, the spray applications were restricted within a 1.0-m strip, a 0.5-m strip on each side of the tree.

Each year during the growing season and immediately before reapplication of glyphosate, weed growth within the treatment area (10 m²) was visually estimated to the nearest 1% to indicate natural weed pressure at various times over the course of the experiment. Periodic measurements were made in each of four 0.1-m² quadrants selected randomly with each plot. The weed species growing within each treatment were also recorded.

Trunk diameter at 30 cm above the ground was measured each spring (late April to early May) beginning the year of planting (1998 until 2003 for all treatment trees). A 30-leaf sample for each treatment and replicate was collected in mid-July, 1999 to 2003, from the midportion of extension shoots of the current year’s growth. All samples were oven-dried at 65 °C and ground in a stainless steel Wiley mill (A.H. Thomas, Co., Philadelphia, PA). From 1999 to 2001, a 250-mg subsample was digested for 0.75 h on a block digester at 350 °C in a H₂SO₄ solution containing K₂SO₄ and HgO. Nitrogen in the digest was determined through the formation of an ammonia-salicylate complex and P was determined through the formation of a phosphomolybdenum blue complex (Technicon Autoanalyzer II Industrial Method No. 329-74W/A; Technicon, Elmsford, NY). After 2001, leaf N was determined using a LECO FP-528 combustion analyzer (St. Joseph, MI). An oven-dried sample of 0.12 to 0.13 g was ignited in the induction furnace. The LECO FP-528 was operated using high gas flow rates, a combustion temperature of 950 °C, and thermal conductivity detection to determine sample N content (Sweeney and Rexroad, 1987). One-gram samples were also dry-ashed at 475 °C and dissolved in 0.5 M HCl before determination of Ca, Mg, and K (1999 to 2001) and Mn, Zn, Fe, and Cu (2000 to 2001) by atomic absorption spectrophotometry. In 2002 to 2003, 0.5-g samples were dry-ashed at 525 °C and dissolved in 1.2 M HCl before determination of Ca, Mg, K, Mn, Fe, and Cu by atomic absorption and P by inductively coupled argon plasma spectrophotometry.

Annual yield and number of fruit at commercial harvest was measured for each treatment and replicate, 1999 to 2003 (27 Sept., 20 Sept., 19 Sept., 18 Sept., 5 Sept., respectively) and expressed on a per-tree basis.

Analysis of variance using PROC GLM (SAS Institute, Inc., 1989) was conducted on measured variables and mean separation was performed using Duncan’s multiple range test. Weed coverage percent data were transformed using the arcsine function; however, treatment differences were similar between transformed and untransformed values, so tabulated means were derived from untransformed values. Analysis of covariance was performed on mean fruit weight to evaluate the treatment effects on mean fruit weight at harvest independent of crop load (Marini, 2002). These data are referred to as “mean adjusted fruit size.” Single

degree-of-freedom orthogonal comparisons were performed to evaluate the specific effects of dichlobenil herbicide (Treatment 2 versus 3), shredded paper (Treatment 2 versus 4), and ground covers (Treatments 1 through 4 versus 5 through 8), respectively.

Results and Discussion

General leaf nutrition. Leaf N, P, Ca, Zn, Cu, and Mn concentrations were considered adequate for apple tree growth (British Columbia Ministry of Agriculture and Food, 2007) and with the exception of Mn (Table 1) were inconsistently affected by treatments (data not shown).

Leaf N was always above the 19 to 24 g·kg⁻¹ [dry weight (DW)] deficiency threshold for apple. The lack of significant treatment effects on leaf N levels contrasts with previous research demonstrating a decline in leaf N associated with applications of paper mulch with spray-on mulch potentially contributing 24 g N/kg (DW), equivalent to 288 g N/tree over a 5-year period when fertigation contributed 1200 g N/tree (Neilsen et al., 2007). This suggests that tree N status was predominantly influenced by the annual fertigation applications rather than by treatment differences associated with variation in N additions or mineralization.

Leaf P concentration ranged from 1.59 to 1.67 g P/kg (DW) throughout the study and were affected by treatments only in 2003, when trees with the HV ground cover treatment had the highest P concentrations (1.68 g·kg⁻¹ DW), whereas trees with the SM plus SOP had the lowest (1.53 g·kg⁻¹ DW) leaf P levels (data not shown).

Leaf Mg concentrations did not fluctuate widely between years and among treatments. In 2 of the 5 years, leaf Mg levels were significantly higher in the SC ground cover treatment, which was associated with a decreased K concentration (Table 2).

Leaf Ca, Zn, and Cu concentrations were not consistently affected by treatments (data not shown) during the study period. Despite the high Ca concentration of the mulch (Neilsen et al., 2007), no immediate plant benefits indicated by increased leaf Ca could be attributed to its use. This is consistent with other research indicating that plant levels of Ca are more affected by plant physiological process than available soil Ca (Himelrick and McDuffie, 1983).

There was a significant treatment effect on leaf Mn concentration (Table 1). WC ground cover treatments consistently had the highest leaf Mn levels, whereas SM treatments had the lowest leaf Mn levels. In 2000, there was a significant effect of dichlobenil on leaf Mn concentration, and in 2001 and 2003, there was a significant effect of ground covers on leaf Mn concentration. Because soil Mn availability increases with decreasing pH (Neilsen and Neilsen, 2003), the higher leaf Mn among the WC treatment specifically and ground cover treatments generally, are most likely associated with changes in soil pH as a result of differences in N mineralization rates among these treatments in comparison with the SM treatments.

Leaf and soil potassium. Leaf K was affected by treatments in 2 of 5 years. In 2001, trees receiving spray mulch as well as the HV and rye cover crop treatments had the highest concentration of leaf K, whereas the WC and SC treatments had the lowest leaf K levels in the range of 8.4 to 12.2 g·kg⁻¹, considered below the critical level of 13 g·kg⁻¹ for the region (Table 2). Tree growth, yield, and fruit quality responses to K fertigation below 13 g·kg⁻¹ have been reported previously for high-density apple orchards (Neilsen et al., 2007). In 2001 and 2002, there was a significant positive response in leaf K among trees receiving SM; in contrast, in 2002, trees with cover crop treatments had markedly lower K levels, which were all considered deficient. By 2003 (Year six) leaf K levels for all but one treatment (HV) were considered deficient for optimal plant growth but not statistically different from one another. This is consistent with other research demonstrating a decline in leaf K to deficient values after several years of drip fertigation of apples on coarse-textured

soils (Neilsen et al., 2000) but in contrast to mulch studies in which increased K was observed in apple and peach (Baker, 1949; Wander and Gourley, 1943). The higher leaf K levels associated with the spray mulch between 2001 and 2002 were likely affected by improved surface soil moisture retention beneath mulches (Neilsen et al., 2003b) resulting in elevated soil moisture contents and a wider distribution of water applied by drip emitters (Neilsen et al., 2007). An estimate of the total amount of K applied as a consequence of the SM (Treatments 2 and 3) and SOP (Treatment 4) treatments was 1.7 g K/tree (5.6 kg·ha⁻¹) and 16.7 g K/tree (56 kg·ha⁻¹), respectively, over the 5-year period of the experiment. Given the similar leaf K concentrations between the glyphosate control and SM or SOP treatments, any contribution of K through the organic mulch amendments was apparently not readily available for plant uptake. Alternatively, the effectiveness of mulching in improving the K nutrition of apple trees has previously been attributed to enhanced root

Table 1. Leaf manganese (mg·kg⁻¹) as affected by different orchard floor vegetation management systems, 2000 to 2003.^z

Orchard floor vegetation management	1999	2000	2001	2002
Glyphosate	46.0 bc	48.0 abc	55.9 ab	45.9 b
Spray-on mulch (SM)	41.6 c	39.8 c	44.1 c	40.2 b
Spray-on mulch plus dichlobenil	50.6 ab	44.7 bc	47.1 bc	43.2 b
Spray-on mulch plus shredded paper (SOP)	43.4 bc	40.3 c	45.8 c	40.7 b
White clover ground cover (WC)	54.6 a	55.7 a	64.4 a	62.9 a
Winter rape/sweet clover ground cover (SC)	45.8 bc	51.1 ab	49.5 bc	50.5 b
Hairy vetch ground cover (HV)	48.8 abc	53.2 a	47.5 bc	50.1 b
Rye ground cover	45.5 bc	49.3 ab	49.1 bc	45.8 b
Statistical significance ^y	*	**	**	**
<i>P</i> value	0.034	0.003	0.002	0.005
Contrasts (<i>P</i> value)				
Effect of dichlobenil	0.021	0.239	0.524	0.596
Effect of shredded paper	0.641	0.888	0.726	0.930
Effect of ground covers	0.087	<0.0001	0.064	0.001

^zAverage values with the same letter within a given column are not significantly different according to Duncan's multiple range test at *P* = 0.05.

^yNS, *, **, *** indicates non-significant and significant differences at *P* = 0.05, *P* = 0.01, and *P* = 0.001, respectively.

Table 2. Leaf potassium (g·kg⁻¹) as affected by different orchard floor vegetation management systems, 1998 to 2003.^z

Orchard floor vegetation management	1999	2000	2001	2002	2003
Glyphosate	13.4	12.6	11.0 bc	12.9 ab	11.1
Spray-on mulch (SM)	14.8	14.2	13.8 a	14.4 a	12.1
Spray-on mulch plus dichlobenil	14.7	13.5	12.5 ab	14.8 a	11.2
Spray-on mulch plus shredded paper (SOP)	14.2	13.6	12.5 ab	13.4 ab	10.8
White clover ground cover (WC)	13.8	13.4	12.1 abc	11.1 bc	9.9
Winter rape/sweet clover ground cover (SC)	12.6	11.2	10.3 c	8.4 c	10.4
Hairy vetch ground cover (HV)	14.3	13.3	13.3 a	12.2 ab	13.6
Rye ground cover	14.9	13.0	12.5 ab	11.4 b	11.6
Statistical significance ^y	NS	NS	*	**	NS
<i>P</i> value	0.3009	0.2405	0.0376	0.0016	0.0831
Contrasts (<i>P</i> value)					
Effect of dichlobenil	0.869	0.553	0.234	0.793	0.431
Effect of shredded paper	0.523	0.584	0.228	0.495	0.243
Effect of ground covers	0.479	0.171	0.442	<0.0001	0.903

^zAverage values with the same letter within a given column are not significantly different according to Duncan's multiple range test at *P* = 0.05.

^yNS, *, **, *** indicates non-significant and significant differences at *P* = 0.05, *P* = 0.01, and *P* = 0.001, respectively.

growth (Boynton and Oberly, 1966) and biological activity (Forge et al., 2003). Whether the decline and deficiency in leaf K among the cover crop treatments could have been overcome through annual supplemental applications of K is a question of interest for future research. In an adjacent cherry experiment on the same soil series, annual fertigation application of 8 to 20 kg K/ha was sufficient to maintain a Mehlich-1 extractable K concentration at 199 mg K/kg (123% of average values for the soil series). Mehlich-1 K declined to 95 mg K/kg (59% of average values) in drip-irrigated plots unfertilized with K after 7 years. There was no evidence of soil K decline under microjet fertigation. It would have been useful to undertake detailed soil K measurements at the end of the apple experiment to assess the spatial and depth variability of extractable soil K among cover crops and mulches but this was not done.

Overall, mulches were associated with a positive response in K status in the tree but insufficiently to prevent low K levels after 5 years. Furthermore, the cover crops evaluated in this study were not beneficial in extracting and recycling K in soil sufficiently to prevent leaf K deficiency from developing, perhaps because of shallow rooting systems. In the long term, fertigating K rather than depending on cover crops to recycle K would be the most effective orchard management strategy to maintain tree K status when growing apples in coarse soils in arid regions. Wetting a larger area of the orchard floor by use of a microjet or other forms of sprinkler irrigation will also maintain tree K status where availability of sufficient water is not an issue.

Tree vigor, yield, and crop load. Tree growth, as represented by annual changes in TCA, was significantly influenced by the various orchard floor vegetation management systems in all 6 years except 1999 (Fig. 1). After the second year of planting (1999), trees receiving spray mulch generally grew more rapidly than trees receiving the ground cover treatments, although these trees had similar K levels that year. Trees receiving the glyphosate treatment had relatively poor but comparable growth to the SC and WC cover crop treatments. After 6 years of growth (2003), trees receiving any of the SM treatments (Treatments 2, 3, and 4) had consistently greater growth ($P < 0.0001$) than any of the cover crop treatments. Growth response in trees receiving the winter rape and sweet clover cover crop treatments was particularly poor, representing $\approx 81\%$ to 82% , respectively, of the growth observed from trees receiving the SM alone (Treatment 2) treatment.

Significant treatment effects on fruit yields with each of the 5 production years (1999 to 2003) were also observed. Based on orthogonal contrasts, ground cover effects (every year) followed by the addition of shredded paper (4 of 6 years) had the greatest effect on annual yield (Table 3). Within an individual year, yield per tree was variable but was consistently greatest from the SM-treated trees and least from SC-treated trees. As a result, cumulative yields (1998 to 2003) were highest from trees receiving any of the SM treatments

or glyphosate treatment; intermediate from trees that had the WC, HV, and rye ground cover treatments; and lowest from trees receiving the SC treatments ($P < 0.0001$).

Fruit size, adjusted for differences in crop load using covariate analysis (Table 4), was also highly influenced by the treatment regimes in all years. Based on orthogonal contrasts, ground cover treatments had the greatest influence on fruit size. Overall, fruit size was greatest for the SM and glyphosate treatments, although in 2003, fruit size was greatest from trees receiving the HV and rye treatments. In 1 of 5 years, there was a significant shredded paper effect (2001) and dichlobenil effect (2003) on fruit size, respectively. Overall fruit size across all years was similar for all the SM,

glyphosate, and HV treatments, but significantly smaller ($P < 0.0001$) in the remaining cover crop treatments.

Ground cover treatments were associated with the lowest crop loads between 2000 and 2003 (data not shown). The effect of SM treatments were inconsistent across years, whereas in 4 of 5 years, trees receiving the glyphosate treatment were among those which had the greatest crop loads. In 4 of 5 years, there was a significant ground cover effect on crop load (2000 to 2003), whereas in 1 of 5 years, there was a significant shredded paper (1999) and dichlobenil effect (1999) on crop load, respectively.

In the past, increased tree vigor has generally been associated with various types of

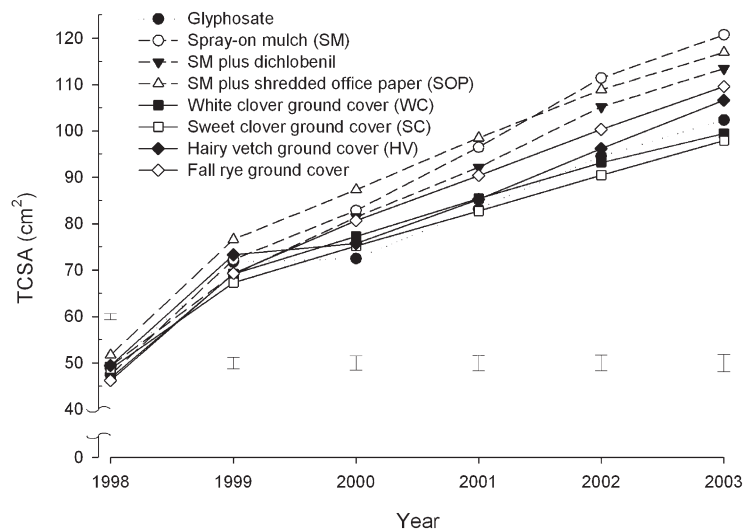


Fig. 1. Trunk cross-sectional area (cm^2) as affected by different orchard floor vegetation management systems, 1998 to 2003. Error bars represent SE of the means for each year.

Table 3. Tree yield (kg/tree) as affected by different orchard floor vegetation management systems, 1999 to 2003.^z

Orchard floor vegetation management	1999	2000	2001	2002	2003	1999–2003
Glyphosate	0.8 ab	4.8 b	5.9 cd	7.6 a	9.8 cd	28.8 a
Spray-on mulch (SM)	0.6 cd	4.5 b	6.8 a	6.2 c	12.7 a	30.8 a
Spray-on mulch plus dichlobenil	0.8 abc	5.2 ab	7.4 a	6.0 cd	11.7 ab	31.0 a
Spray-on mulch plus shredded paper (SOP)	0.9 a	5.7 a	6.7 ab	7.1 ab	10.5 bc	30.9 a
White clover ground cover (WC)	0.8 ab	4.5 b	5.1 de	5.3 d	9.4 cde	25.1 b
Winter rape/sweet clover ground cover (SC)	0.5 d	2.9 c	4.4 e	6.0 cd	8.2 e	22.0 c
Hairy vetch ground cover (HV)	0.8 abc	3.5 c	5.8 cd	6.3 bc	8.9 de	25.4 b
Rye ground cover	0.6 bcd	3.3 c	6.0 bc	6.5 bc	9.0 cde	25.5 b
Statistical significance ^y <i>P</i> value	*** <0.0001	*** <0.0001	*** <0.0001	*** <0.0001	*** <0.0001	*** <0.0001
Contrasts (<i>P</i> value)						
Effect of dichlobenil	0.037	0.085	0.102	0.642	0.165	0.844
Effect of shredded paper	0.001	0.001	0.772	0.012	0.002	0.892
Effect of ground covers	0.014	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zAverage values with the same letter within a given column are not significantly different according to Duncan's multiple range test at $P = 0.05$.

^yNS, *, **, *** indicates non-significant and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

mulch materials and attributed to reductions in water stress, weed competition, and extremes in soil temperature (Hogue et al., 2003; Neilsen et al., 2004). Maintenance of shredded paper mulch in a daily, drip-irrigated, high-density ‘Spartan’ apple orchard resulted in a 50% increase in trunk diameter and an 80% increase in per-tree yield relative to trees growing in herbicide strips (Neilsen et al., 2003a). For the ‘Gala’ trees in this experiment, trunk diameter was also significantly increased in mulch relative to glyphosate plots but increased yield, as observed for ‘Spartan’ trees, was not measured. Early tree growth in the formative years of production can have a significant influence on cumulative yield during the first 5 bearing years as demonstrated in this study. However, sustaining such yield benefits in the longer term will be difficult without the addition of K fertilizer. There was no notable visual difference in fruit disorders or appearance between the treatments throughout the study; however, a systematic assessment of fruit quality characteristics at harvest and after storage is recommended in future studies of this type to fully assess the impact of any yield increases associated with treatments.

Weed control. Significant treatment differences in weed control were observed over the course of the experiment (Table 5). Weed control, as expressed by percentage surface area covered by weeds, varied among treatments and fluctuated in relation to when the measurements were made during the growing season. The rye cover crop consistently had the lowest amount of weed growth, whereas the WC cover crop had the most (in four of the eight measurement dates). The SM plus SOP and SM plus dichlobenil had comparable weed control as the rye cover crop. Although the glyphosate treatment provided good weed control immediately after application, it was relatively short-lived resulting in significant weed and grass regrowth and the need to make repeat applications. Over the course of the eight assessment periods (representing four growing seasons), the effect of dichlobenil and the additive effect of SOM with the SM were both significant in 1999 and 2001. During the same time, the effect of ground covers was significant in all eight assessment periods, clearly a result of the efficacious rye cover crop treatment and its allelopathic effect on weed growth (Barnes and Putnam, 1983).

Qualitative assessment of the weeds species indicated that Chickweed [*Stellaria media* (L.) Vill.] was common in all cover crop treatments; Whitlowgrass (*Draba verna* L.) was common in the WC and SC treatments; Downy Brome (*Bromus tectorum* L.) was common in the WC, SC, and HV treatments; and Henbit (*Lamium amplexicaule* L.) was common in the WC, SC, and HV treatments and to a lesser extent the rye treatment (data not shown). The propensity for weed escapes in the ground cover treatments was closely associated with cover crop establishment and initial growth. The stands of white clover and winter rape were particularly difficult to establish, and therefore their consistency as suitable ground covers were diminished irrespective of their competitive influence on tree vigor and yield.

Conclusions

A significant response to SM treatments in terms of improved tree growth and annual yields and reduced weed growth was achieved in this study. However, the living mulch cover crops were sufficiently competitive to diminish tree vigor and yield, although weed growth

Table 4. Mean adjusted fruit size (g) (adjusted for crop load) as affected by different orchard floor vegetation management systems, 1999 to 2003.^z

Orchard floor vegetation management	1999		2000		2001		2002		2003		Overall 5-yr mean
Glyphosate	158.8	b	196.0	a	175.2	ab	196.5	ab	174.4	b	181.7
Spray-on mulch (SM)	165.1	ab	193.2	a	181.1	ab	188.3	abc	172.1	b	178.4
Spray-on mulch plus dichlobenil	161.6	ab	199.6	a	184.0	a	202.0	a	169.7	bc	181.9
Spray-on mulch plus shredded paper (SOP)	159.3	ab	197.1	a	169.4	bc	196.6	ab	169.1	bc	178.4
White clover ground cover (WC)	157.9	b	197.3	a	173.9	ab	180.4	cd	155.2	d	170.7
Winter rape/sweet clover ground cover (SC)	141.5	b	179.4	b	171.4	abc	169.9	d	166.4	c	171.3
Hairy vetch ground cover (HV)	168.1	a	183.7	b	180.8	a	182.0	bcd	178.4	a	182.3
Rye ground cover	155.8	b	186.2	b	161.2	c	180.2	cd	177.5	a	173.7
Statistical significance ^y	***		***		**		***		***		***
P value	<0.0001		<0.0001		0.002		<0.0001		<0.0001		<0.0001
Contrasts (P value)											
Effect of dichlobenil	0.386		0.068		0.625		0.024		0.383		0.213
Effect of shredded paper	0.158		0.270		0.050		0.171		0.268		0.998
Effect of ground covers	0.009		<0.0001		0.058		<0.0001		0.150		<0.0001

^zAverage values with the same letter within a given column are not significantly different according to Duncan’s multiple range test at $P = 0.05$.

^yNS, *, **, *** indicates non-significant and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

Table 5. Weed coverage (%) in 1999 to 2003 as affected by different orchard floor vegetation management systems.^z

Orchard floor vegetation management	4 June 1999		8 May 2001		4 July 2001		23 Apr. 2002		2 Oct. 2002		22 May 2003		7 July 2003		29 Aug. 2003	
Glyphosate	78	a	5	bc	21	a	32	bc	5	b	8	bc	8	b	7	b
Spray-on mulch (SM)	73	a	27	a	3	bc	20	cde	3	b	1	c	2	b	2	b
Spray-on mulch plus dichlobenil	6	de	5	bc	1	d	4	e	2	b	1	c	3	b	3	b
Spray-on mulch plus shredded paper (SOP)	22	cd	5	bc	1	cd	8	e	2	b	0	c	2	b	2	b
White clover ground cover (WC)	44	b	10	b	17	ab	47	ab	24	a	27	a	23	a	27	a
Winter rape/sweet clover ground cover (SC)	37	bc	1	c	16	ab	27	cd	5	b	32	a	1	b	8	b
Hairy vetch ground cover (HV)	29	bc	5	bc	9	bc	58	a	1	b	14	b	1	b	9	b
Rye ground cover	0	e	1	c	8	cd	12	de	4	b	2	c	1	b	3	b
Statistical significance ^y	***		***		***		***		***		***		***		***	
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
Contrasts (P value)																
Effect of dichlobenil	<0.0001		<0.0001		0.716		0.062		0.902		0.972		0.904		0.848	
Effect of shredded paper	<0.0001		<0.0001		0.716		0.138		0.773		0.833		0.872		0.962	
Effect of ground covers	0.0002		0.0004		0.0021		<0.0001		0.0090		<0.0001		<0.0001		<0.0001	

^zAverage values with the same letter within a given column are not significantly different according to Duncan’s multiple range test at $P = 0.05$.

^yNS, *, **, *** indicates non-significant and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

within the rye cover was markedly reduced by its allelopathic effect. In addition, mulch treatments were unable to prevent low K levels after 5 years, even with the addition of K from the organic mulches. Recycling of K by cover crops was furthermore insufficient to avoid the development of low leaf K levels. Clearly a treatment response in tree growth and yield was obtained despite inadequate K nutrition that became worse with time. Yield responses to the SM and living mulch treatments are therefore likely associated with enhanced tree growth as a result of improved soil moisture or other treatment effects on the soil environment. Annual supplemental fertigation of K appears necessary to maintain sufficient long-term tree vigor and yield when using mulches or cover crops in intensive, drip-irrigated apple orchards grown on coarse soils, even when initial soil K levels appear adequate.

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