Long-term Effects of Four Groundcover Management Systems in an Apple Orchard

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Abstract. Groundcover management systems (GMSs) are essential for fruit production, but very few long-term studies have evaluated orchard GMS sustainability. We evaluated four GMSs—pre-emergence soil-active herbicides (PreHerb), post-emergence herbicide (PostHerb), a turfgrass cover crop (Sod), and hardwood bark mulch (Mulch)—in an apple (*Malus domestica* Borkh.) orchard over 16 years of continuous observation. There were no consistent long-term trends in fruit yields among GMSs, although during the first 5 years, yields were lower in trees on Sod. Tree growth was greater in PostHerb and Mulch than in Sod during the first 5 years, and during the next decade, trees in Mulch plots were consistently larger than in other GMSs. Total soil nitrogen (N) and carbon (C) content, C-to-N ratios, and essential plant nutrients were much greater in the Mulch soil after 16 years of treatments. Long-term responses of trees to groundcover vegetation indicated that apple trees respond adaptively to compensate for weed and grass competition. Year-round elimination of surface vegetation with residual soil active herbicides may be unnecessary or even detrimental for orchard productivity and soil fertility in established orchards. Post-emergence herbicides that reduce weed competition primarily during the summer months may offer an optimal combination of weed suppression and soil conservation.

Groundcover management systems are important in fruit production to maintain soil tilth and fertility, reduce weed competition for soil nutrients and water, moderate soil temperature and moisture extremes, provide a habitat for beneficial arthropods, and minimize soil erosion—helping growers to achieve and sustain orchard productivity over production cycles spanning many decades. Since the 1950s, most fruit growers in North America and Europe have maintained orchard drive lanes with mowed sodgrass and treated tree rows with various herbicides to suppress or eliminate weeds (Merwin, 2003a). With increased interest in reducing herbicide applications and conserving soil resources, alternative GMSs are being adopted by growers (Hogue and Neilsen, 1987), and questions are being raised about the long-term sustainability of various orchard GMSs.

Previous research has evaluated and compared different GMSs including herbicides, mechanical cultivation, turfgrasses, geotextiles and biomass mulches, and legume cover crops (Hogue and Neilsen, 1987; Merwin, 2003a; Merwin and Stiles, 1994). These studies have shown substantially different GMS effects on soil chemical, biological, and physical properties (Merwin et al., 1994; Sanchez et al., 2007; St. Laurent et al., 2008) as well as differential effects on root-zone

microbial communities and tree root development (Morlat and Jacquet, 2003; Yao et al., 2005, 2009). However, most GMS studies have been short-term, spanning just a few years; only a handful have evaluated the long-term (i.e., a decade or more) effects of GMSs on tree yield, growth, biomass allocation, and soil characteristics (Glenn and Welker, 1996; Klik et al., 1998; Layne et al., 1994; Morlat, 2008; Morlat and Chaussod, 2008; Morlat and Jacquet, 2003; Tasseva, 2008). Longer studies that span the productive lifetime of commercial orchards are necessary to assess gradual changes over time as well as year-to-year variability in perennial crop systems.

To evaluate and compare long-term GMS effects, we initiated a study in 1992 with a commercially managed planting of apple trees under four different GMS treatments in upstate New York. The underlying objectives of this study were to determine the impacts of various GMS treatments on tree growth, nutrition, and production and to ascertain the effects of various GMS treatments on soil physical and edaphic conditions over several decades.

Materials and Methods

Experimental site. The experimental site is a moderately sloped 0.8-ha orchard on the east side of Cayuga Lake near Ithaca, NY (lat. 42°49' N, long. 76°49' W; annual mean precipitation 76 cm). The soil at this site is a glacial till silty clay loam (Ovid series, mixed mesic Glosaquic Hapludalf). The site

was prepared for planting in 1990 by removing a previous old apple orchard and installing a replicated grid of 12 isolated subsoil drainage lysimeters. During 1991, the entire site was ploughed, 8 MT·ha⁻¹ of dolomitic lime was applied, the soil was cultivated thoroughly with a disc harrow, and a red fescue (*Festuca rubra* L.) turfgrass was sown at 50 kg seed/ha in Aug. 1991. Apple trees ('Empire' on 'M.9'/'MM.111' interstem rootstocks) were planted in Apr. 1992 at 3 × 6-m spacing. Four GMS treatments were set up in 2-m wide strips within tree rows and have been maintained continuously since 1992. The GMSs were assigned randomly to 12 plots with three replicates of each treatment. The experimental units were 9-m wide across the slope and 25-m long downslope, each including four parallel tree rows containing 20 to 24 trees separated by a 4-m wide grass drive lanes of the same mowed red fescue sod throughout the site (Merwin et al., 1996). Trees were irrigated weekly for 8 h when droughts occurred during nine growing seasons using microsprinklers that provided 32 L·h⁻¹ over a 4-m² circular area centered on each tree.

Groundcover management system treatments. Four GMS treatments were established in May 1992 and maintained in 2-m wide strips centered on the tree rows as follows: 1) PreHerb—a pre-emergence soil-active herbicide treatment consisting of three tank-mixed herbicides (glyphosate, norflurazon, and diuron) at 2.0, 3.0, and 2.5 kg a.i./ha, respectively, applied in mid-May each year to keep the tree rows weed-free all year long; 2) PostHerb—a post-emergence herbicide treatment consisting of glyphosate applied at a rate of 2 kg a.i./ha in mid-May and July each year to suppress weeds during the growing season; 3) Sod—the red fescue turfgrass originally seeded in 1991, eventually comprising a mixture of various grass and broadleaf species that was mowed monthly at 6-cm height from April to October each year; and 4) Mulch—a 15-cm thick layer of shredded composted hardwood (a mixture of *Acer*, *Quercus*, *Juglans*, *Fraxinus*, and *Tilia* sp.) bark mulch applied in 1992, 1995, 1998, 2000, 2002, and 2005. From 1996 onward, glyphosate herbicide was spot-applied to the Mulch plots in mid-May as needed to suppress emergent perennial weeds in this treatment (Oliveira and Merwin, 2001; Yao et al., 2005).

During the establishment years of this orchard, ammonium–nitrate fertilizer was applied to the soil beneath trees in all GMSs at rates of 30, 45, and 65 kg N/ha in mid-Apr. 1992, 1993, and 1994, respectively. In May 2005, 22.7 kg superphosphate (0N–45P–0K) was applied as a side-dress soil application beneath all trees to evaluate N uptake and allocations after 13 years of each treatment. To compensate for nutrient loss through crop removal after the orchard came into full production, 400 kg·ha⁻¹ of sulfate of potash–magnesia (0 N: 0 P: 22 K: 11 Mg) was applied to soil beneath all trees in November each year from 1996 onward. Foliar sprays of urea (2 kg N/ha), boron (0.6 kg B/ha), and zinc (2 kg Zn/ha) were applied annually

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from 2001 to 2008 at the pink or petal fall growth stages as recommended for commercial orchards in New York (Stiles and Reid, 1991).

Tree growth and fruit yield. Tree trunk cross-sectional area (TCSA) was recorded annually during the dormant season (usually in March) at a permanently marked height (0.45 m aboveground) to estimate annual and cumulative increases in tree size. Fruit yield was recorded each year from 1994 to 2008, as harvested fruit weight (kilograms) per tree, number of fruit per tree, average fruit size (grams), and total yield per tree (harvested + dropped fruits in kilograms per tree). Fruit yield data were collected from the centermost 12 trees in each plot (to minimize edge effects) and averaged to represent a treatment mean for respective GMS treatments. Yield efficiency of the trees in each GMS treatment was calculated as fruit yield (kg/tree) per TCSA (cm²).

¹⁵N tracer application and tree biomass excavation. During the 2000 growing season, the soil beneath one tree in the middle of each plot received three-way split (May, June, and September) applications of 0.17 g of 99% enriched K¹⁵NO₃ (for a cumulative total of 0.5 g K¹⁵NO₃ per tree). The amount of ¹⁵N applied to each tree was kept to a minimum because our main intent was to trace allocations of ¹⁵N to various parts of trees that had not received N fertilizer for the past 5 years, and we did not intend to estimate N fertilizer use efficiency. In mid-Apr. 2001, the dormant trees to which ¹⁵N had been applied the previous year were excavated carefully to obtain as much of their shoot and root systems as possible. Each tree was dissected into different size classes of roots: fine roots (less than 1-mm diameter), secondary roots (1 mm to 1 cm) and main roots (1 to 4 cm), shoots and trunk tissue, and both fresh and dry weights of each tissue subsample were determined.

Total N (kg/tree) and the atom per mil ¹⁵N were determined by isotope ratio mass spectrometry at Isotope Services Laboratory (Los Alamos, NM). The δ¹⁵N values were calculated using the known atmospheric N isotope ratio (3676 ± 8.1) as a standard (Hayes, 1983).

Soil analyses. Soil samples were collected during midsummer with a 2-cm-diameter metal core from 0- to 20-cm depth. Samples were sent to the Cornell University Nutrient Analysis Laboratory and analyzed for plant-available nutrients by inductively coupled argon plasma spectroscopy; soil N content was determined by Kjeldahl digestion from 1992 to 1998, and soil C and N were determined by Dumas combustion from 1999 to 2007. Macro- and micronutrients were extracted in Morgan's solution (0.72 N NaOAc + 0.52 N CH₃COOH, buffered at pH 4.8) and soil organic matter was determined by loss on ignition at 550 °C.

Data analysis. There were significant interactions between years and GMS treatments when data were analyzed using a repeated-measures model, so means comparisons were evaluated within years using a one-way analysis of variance for a completely randomized design with three replicates (JMP, Version 7; SAS Institute Inc., Cary, NC). When significant effects were indicated within years, means were compared using Tukey's honestly significant difference at *P* = 0.05, unless otherwise noted in text and tables. Trends within treatments were analyzed using a random intercept model, which accounted for variability between and within plots. To evaluate multiyear trends, the data were separated into two periods for yield analyses—one from 1994 to 2000 (the orchard establishment years) and a second period from 2001 to 2008 (the mature bearing years). For tree growth analyses, the two time periods were 1992 to 2000 and 2001 to 2008.

Results

The GMS effects on yields were complex during the 15 years of this study (Fig. 1), and there were significant treatment differences in 7 of 15 years for fruit production. During the establishment years (1994 to 2000), the Sod treatment trees were less productive than PostHerb trees (*P* = 0.1); during the mature bearing years (2001 to 2008), there was no significant main effect of GMS, although yields were numerically greater in the PostHerb and Mulch than in the Sod and PreHerb treatments. In 2002 and 2005, yields were reduced substantially in all GMSs because of severe frost damage during bloom in 2002 and heat stress during the post-bloom chemical thinning period during 2005 that led to excessive fruit abscission in all treatments. The GMS effects on cumulative yield were more consistent throughout the years (Fig. 2). In 7 of the 9 years with significant differences among treatments, cumulative yields of trees in Sod plots were less than those of PostHerb trees.

During the first 3 years after planting, TCSA was greater in PostHerb than in Sod plots (Fig. 3). Beginning in 1998, the TCSA of trees in the Mulch treatment surpassed that in Sod and PreHerb during 8 of 11 years. The rate TCSA increase in Mulch trees was twofold greater during the second period (2001 to 2008) than during the earlier time-span (*P* = 0.015).

There were treatment effects on yield efficiency during the initial bearing years (Fig. 4). In 1995, yield efficiency of trees in Sod was less than those in Mulch. In 1996, yield efficiency in Sod was less than in PostHerb. From 1997 to 2008, there were few significant yield efficiency differences among treatments, but yield efficiency was numerically greater in PostHerb treatment trees and lower in Mulch plot trees during

Fig. 1. Average yield (kg fruit/tree) from 1994 through 2008 for trees in each groundcover management system treatment. Letters were generated from Tukey's honestly significant difference test at *P* ≤ 0.05 for 1995, 1996, 1998, and 2003 and *P* ≤ 0.1 for 1994, 1999, and 2001.

Fig. 2. Cumulative yield (kg fruit/tree) from 1994 through 2008, for trees in each groundcover management system treatment. Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$ for 1994, 1995, and 1996 and $P \leq 0.1$ for 1999, 2000, 2001, 20002, 2003, and 2006.

Fig. 3. Cumulative mean tree trunk cross-sectional area (TCSA) (cm²) from 1992 through 2008. Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$ for 1993, 1999, 2004, 2005, 2006, 2007, and 2008 and $P \leq 0.1$ for 1992, 1994, 1998, 2000, 2002, and 2003.

most of those 12 years. In 2002 and 2005, yield efficiency was unusually low in all treatments because of weather-related crop losses those years.

The aboveground dry weight biomass allocations of excavated 10-year-old apple trees did not differ consistently among GMS treatments in 2001 (Fig. 5A). Belowground biomass allocations were significantly different only for secondary roots with Mulch trees producing more secondary root biomass than Sod and PreHerb trees (Fig. 5B). Total tree biomass was numerically greater in the PostHerb and Mulch compared with Sod and PreHerb treatments, but this trend was not

significant among the four GMSs despite the differences observed in TCSA and cumulative yields.

Total aboveground N content of excavated trees was similar among GMSs (Fig. 6A). For belowground N content, fine roots contained more N in the Mulch and PostHerb than in Sod trees (Fig. 6B). For secondary roots, Mulch trees had greater N content than trees in PreHerb and Sod. In contrast to total N content, in our ^{15}N tracer uptake observations, the aboveground tissue ^{15}N enrichment was greater in PreHerb trees than Sod or Mulch trees, except for trunk and scaffold biomass (Fig. 7A). For belowground tissues,

the $\delta^{15}\text{N}$ ratios were higher in PreHerb than Mulch, except for main roots (Fig. 7B).

Total soil N and C content and C-to-N ratios were significantly greater in the Mulch than all other treatments from 1999 to 2007, but there were no differences observed among the other GMSs (Fig. 8). There were sustained trends in the relative availability of essential plant nutrients among GMSs during 15 years of observations (Table 1). There were few differences among treatments in soil nutrient content during the initial years of this study. Over the longer term, GMS treatments influenced soil nutrient supply and many essential plant nutrients were more

Fig. 4. Yield efficiency ($\text{kg}\cdot\text{cm}^{-2}$) of fruit trees from 1994 through 2008. Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$ for 1994, 1995, 1996 and 2003 and $P \leq 0.1$ for 2000.

Fig. 5. (A–B) Dry weight allocation (kg) by section for roots and shoots from whole tree harvest. One tree from each plot was uprooted and divided into sections in Apr. 2001. Subsamples from each section were weighed fresh and dry, and total dry weight for each section was calculated. Letters refer to mean separation for secondary roots and were generated from Tukey's honestly significant difference test at $P \leq 0.05$.

available in Mulch treatment soil than in other GMSs. Soil organic matter content increased gradually and diverged from other GMSs in the Mulch treatment from 1992 to 2007, although there was some variation attributed to sampling methods from year to year. A layer of partially decomposed mulch interfaced with the mineral soil in Mulch plots. This humic layer was not uniformly distributed in the soil profile, and its spatial variation led to occasional outliers for organic matter

content in our sample cores. When the mulch application frequency decreased after 2002, there was a noticeable decrease on soil organic matter content in that treatment.

Discussion

There are very few long-term reference studies of perennial fruit orchard or vineyard GMSs to compare with the results of our 16-year study. Most short-term studies have

shown that GMS treatments involving herbicides and mulches to suppress tree-row weeds led to increased tree growth and fruit yields during the first 3 to 5 years after planting compared with weedy control treatments or mowed sod covers (Hippes et al., 1990; Merwin and Stiles, 1994; Miller and Glenn, 1985; Pool et al., 1990). As previously reported by others (Robinson and O'Kennedy, 1978; Shribbs and Skorch, 1986; Welker and Glenn, 1989), we also observed reduced yields during the orchard establishment years from 1994 to 2000 in the Sod treatment compared with PostHerb plots (Figs. 1 and 2), but it was noteworthy that this initial trend was not sustained over the longer-term.

Mowed sod covers incorporate more biomass inputs to soil than herbicide-treated plots, but turfgrasses are also more efficient than fruit trees in the uptake and recycling of N and some other plant nutrients (Haynes and Goh, 1980; Sanchez et al., 2003; Yao et al., 2005). The nutrients released from grass residue mineralization are evidently recycled within the grass itself and not readily available to fruit trees (Atkinson, 1980). However, during the final decade of our study, the growth and yields of trees in Sod were not statistically different from trees in the weed-free PreHerb plots during most years, and there were few distinct trends among the GMSs. Yao et al. (2009) reported that apple roots grew deeper and survived longer beneath Sod than PreHerb treatments at this orchard, and Glenn and Welker (1996) noted that peach (*Prunus persica* L.) trees competing with proximate sod covers were stunted during the early years of a 6-year study but adapted to grass competition over time and eventually became more yield-efficient than trees in herbicide-treated weed-free rows. These long-term adaptive responses of mature established fruit trees to differences in surface

Fig. 6. (A–B) Total nitrogen (kg) allocation in sections from whole tree harvest. One tree in each plot that had received three split applications of ^{15}N during the 2000 growing season was uprooted and divided into sections in Apr. 2001. Subsections were dried, weighed, ground, and analyzed for %N. Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$.

Fig. 7. (A–B) $\delta^{15}\text{N}$ ratios in sections of trees from a whole tree harvest. One tree in each plot that had received three split applications of ^{15}N during the 2000 growing season was uprooted and divided into sections in Apr. 2001. Subsamples were dried, weighed, ground, and analyzed for atom. % ^{15}N . Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$.

vegetation, nutrient competition, and differing soil conditions under various GMSs suggest that alternative systems that augment vegetative cover and soil biomass inputs could help to sustain soil resources in orchards without

negative competitive effects on tree health and productivity.

Layne and Jui (1994) noted in a 10-year study of peach rootstocks that trees performing better in the early years after planting

often lagged behind others over the longer-term. Several orchard replant studies have also shown that initial differences in tree growth and yield after different preplant soil treatments became less pronounced or disappeared over successive years (Arneson and Mai, 1976; Mai et al., 1994). Although there were no significant main effects of GMS on tree size in either of the two time periods (orchard establishment and maturity) of our study, trees in the Mulch plots were significantly bigger than those on Sod and PreHerb plots during the last 5 years. Haynes (1980) attributed mulch benefits in orchards to weed suppression during the growing season, but this would not explain why trees grew larger in Mulch than in PreHerb plots at our site. The Mulch system provided adequate weed suppression during the first several years of this study, and for a few months after each renewal of the bark-mulch layer, but over the years, this GMS was invaded by deep-rooted aggressive perennial weeds such as dock (*Rumex* sp.), milkweed (*Asclepias syriaca*), swallowwort (*Cynanchum nigricum* and *C. vincetoxicum*), poison ivy (*Toxicodendron radicans*), wild grape (*Vitis riparia*), and Virginia creeper (*Parthenocissus quinquefolia*). After 1996, annual spot applications of glyphosate herbicide were necessary to suppress these invasive weeds in Mulch plots, and by late summer each year, there were substantial weed populations ($\approx 50\%$ surface coverage) of dandelions (*Taraxacum officinale* Weber), ground ivy (*Glechoma hederacea* L.), white clover (*Trifolium repens* L.), and common groundsel (*Senecio vulgaris* L.) in the Mulch plots. A more likely explanation for the increased cumulative growth of trees in Mulch from 1999 onward was the increased soil organic matter, nutrient availability (Table 1), and more uniform soil water supply throughout most growing seasons under this GMS.

We selected bark mulch for this study thinking that it might increase the duration and decrease the costs that are problematic with mulch GMSs. Hardwood bark is inherently resistant to decomposition, locally available in much of the northeastern United States, and persists longer than other biomass mulches such as hay–straw or grass clippings (Goh and Tutua, 2004; Whitford et al., 1989; Yao et al., 2005). During the initial years of our study, nutrient release from the bark mulch did not increase soil nutrient availability compared with the other GMS treatments. However, by the ninth year (after four applications), Mulch had doubled the content of topsoil organic matter in comparison with other GMSs, which in turn increased availability of other nutrients because of the pivotal roles of organic matter in soil fertility (Diacono and Montemurro, 2010). In a comparable long-term GMS study, Morlat and Chaussod (2008) observed significant increases in soil organic matter after 7 years of applying cattle manure (10 MT/ha/year) and spent mushroom compost (8 MT/ha/year) in a vineyard soil compared with a control treatment without soil biomass amendments, although no significant treatment

Fig. 8. The percent nitrogen (N), percent carbon (C), and C-to-N ratio in soil under four groundcover management system treatments in 1999, 2000, 2001, 2005, and 2007. Letters were generated from Tukey's honestly significant difference test at $P \leq 0.05$.

differences in vine growth or yield were observed during this period of time (Morlat, 2008).

Competition between weeds and fruit trees for nutrients and water can cause substantial growth reductions and yield losses in orchards (McMurtrie and Wolf, 1983). Some other studies have shown that suppressing vegetation beneath trees during the entire growing season had positive effects on tree productivity (Hogue and Neilsen, 1987; Tesic et al., 2007; Welker and Glenn, 1985). However, in our long-term experiment, the trees in PostHerb plots performed as well or better than those in PreHerb plots despite the greater weed surface coverage in PostHerb versus PreHerb tree rows (Figs. 1 to 4). These observations are consistent with previous reports that eliminating weed competition at critical times during the growing season may be as effective as keeping tree rows weed-free throughout the year (Al-Hinai and Roper, 2001; Gut et al., 1996; Smith et al., 2005). Merwin and Ray (1997) also observed that early summer (May and June) weed control was especially critical for newly planted apple trees. Weed competition for N at the beginning of the growing season may decrease the availability of photoassimilates and consequently reduce growth in young trees (Jordan and Jordan, 1981). Weed suppression between harvest and leaf fall reportedly increased spring tree growth the next year, because of the accumulation of carbohydrates in woody tissue during the previous growing season (Roper et al., 1988). These previous reports and our own long-term ob-

servations suggest that year-round elimination of surface vegetation may be unnecessary and even detrimental in orchards, because of potential long-term negative impacts on soil conditions in orchards where tree-row surface vegetation is eliminated with frequent mechanical cultivation or persistent herbicides (Merwin, 2003a; Merwin et al., 1994; Oliveira and Merwin, 2001).

Previous reports of N partitioning and tree-root biomass allocations in relation to GMSs were based on other fruit crops or floor management systems in different soil types and are thus not directly comparable to our results (Morlat and Jacquet, 2003; Parker et al., 1993; Parker and Meyer, 1996; Stefanelli and Perry, 2006). In a related report based on the same orchard, Yao et al. (2009) noted that a greater percentage of tree roots were observed in rhizotron transects from 1- to 20-cm depth beneath trees in the Mulch and PostHerb plots compared with Sod and PreHerb plots and that tree root mortality at shallow soil depths was greater beneath PreHerb than other GMS treatments during a hot, dry summer. In the present study, we observed less dry matter and N partitioning into secondary (1-mm to 1-cm diameter) tree roots in Sod and PreHerb compared with Mulch (Figs. 5 and 6). For Sod, these observations could be attributed to water stress (Glenn and Welker, 1993; Hogue and Neilsen, 1987; Parker et al., 1993) or reduced tree N uptake as a result of low soil N availability (Sanchez et al., 2007; Yao et al., 2005). For PreHerb, the limiting factors may be less favorable root growth conditions as a result of deteriorated soil physical properties

(porosity, bulk density, infiltration capacity, etc.) after 15 years without groundcovers (Goh et al., 2001; Psarras and Merwin, 2000; Yao et al., 2005).

Differences in soil water availability among GMSs can influence fruit tree growth and yields (Glenn and Welker, 1989; Hogue and Neilsen, 1987; Merwin et al., 1994). Trees subjected to water stress may have reduced photosynthetic capacity and restricted carbohydrate supply for growth (Lakso et al., 2005). In our study, irrigation was provided whenever there were extended dry periods, and root-zone soil water content was monitored continuously with time-domain reflectometry probes, which showed few consistent trends or differences in soil water availability among GMS treatments from 1997 to 2007 (data not shown). Previous studies have indicated that irrigation alone cannot compensate for water competition between fruit trees and groundcover vegetation (Glenn and Welker, 1993; Hogue and Neilsen, 1987; Merwin, 2003b; Welker and Glenn, 1985). However, long-term observations in the present study suggest that supplemental irrigation with microsprinklers that provide water to a large enough proportion of the tree root zone could alleviate groundcover competition. This could be one reason for the lack of consistent long-term differences in tree productivity in our study despite substantial differences in soil fertility and physical conditions among the four GMSs.

The ^{15}N tracer observations showed more fertilizer N enrichment ($\delta^{15}\text{N}$) for trees in the two herbicide GMSs compared with those in Mulch and Sod treatment, although this trend was not always consistent. Apple tree uptake of soil N is critical during early summer (May and June) and rapid uptake from current-season N supply occurs from bloom to the end of shoot growth (Cheng and Raba, 2009), a period when weeds are also growing vigorously and likely to be competitive with fruit trees (Al-Hinai and Roper, 2001; Merwin and Ray, 1997). The trees' competitive ability for uptake of soil N was weak compared with groundcover vegetation—indicated by the generally lower ^{15}N enrichment in 1-, 2-, and 3-year-old wood, scaffold branches, and main roots of trees growing in Sod (Fig. 7) compared with PreHerb—in part because the first two applications of ^{15}N occurred during May and June when groundcover competition was presumably maximal. The atom percent ^{15}N in grass and weeds beneath trees spiked after each labeled fertilizer application, and it was greater for weeds in PreHerb and PostHerb than other treatments. During the subsequent growing season, $\delta^{15}\text{N}$ ratios in groundcover vegetations remained two to five times greater than in tree leaves (data not shown). For Mulch trees, the lower $\delta^{15}\text{N}$ values in some sections of above- and below-ground tree biomass may also have reflected tracer dilution by a greater total N pool in Mulch soil and trees compared with the other GMSs (Teravest et al., 2010).

Short-term studies in orchards have shown greater tree-root growth in weed-free plots

Table 1. Long-term effects of groundcover management system treatments on soil nutrient availability (kg-ha⁻¹), organic matter (%), and pH.^z

Variable	1992	1993	1995	2000	2005	2006	2007
NO³⁻							
PreHerb	11.4	47.7 a	19.5	13.1 b	N/D	N/D	2.6 b
PostHerb	11.2	24.6 ab	8.7	12.7 b			5.4 b
Sod	10.8	11.0 b	2.6	12.7 b			4.0 b
Mulch	11.2	11.1 b	4.8	15.7 a			23.9 a
Phosphorus							
PreHerb	1.2	3.2 a	2.8 a	7.1 b	2.1 b	2.2	1.0 b
PostHerb	1.4	2.8 ab	0.7 ab	6.0 b	2.1 b	2.4	1.6 b
Sod	1.0	1.5 b	0.3 b	3.7 b	3.2 b	1.9	1.2 b
Mulch	1.3	2.7 ab	1.1 ab	16.4 a	22.0 a	7.1	10.0 a
Potassium							
PreHerb	122.3 ab	169.5 ab	74.4 ab	375.2	410.2 ab	249.0	190.5
PostHerb	127.5 ab	191.3 ab	74.3 ab	317.3	328.5 b	207.8	214.5
Sod	106.5 b	148.5 b	56.1 b	306.1	420.5 ab	193.5	192.0
Mulch	158.3 a	200.3 a	93.9 a	388.3	595.4 a	264.0	299.3
Calcium							
PreHerb	4,041.0	4,733.3	2,028.1	3,124.8 b	3,216.7 b	3,620.3 b	3,364.5 b
PostHerb	3,192.8	4,284.0	1,509.0	2,639.5 b	3,191.3 b	3,551.3 b	3,060.8 b
Sod	3,291.0	4,107.0	1,525.0	2,284.8 b	3,086.8 b	3,276.8 b	3,087.0 b
Mulch	4,935.0	4,700.3	1,760.7	5,730.7 a	12,799.0 a	8,248.5 a	9,559.5 a
Magnesium							
PreHerb	682.7	912.4 a	418.5	957.6	898.8	810.1 a	862.3
PostHerb	597.4	857.3 ab	367.6	767.2	792.9	772.3 a	805.8
Sod	629.0	799.8 ab	353.2	774.7	889.1	690.5 ab	805.1
Mulch	612.5	705.0 b	342.3	643.7	988.1	544.7 b	760.1
Manganese							
PreHerb	38.6	27.7 b	71.3 b	234.1	58.4 b	44.6 b	26.9 b
PostHerb	36.0	30.0 b	76.0 b	154.6	44.7 b	40.2 b	32.7 b
Sod	31.7	32.0 b	81.8 ab	121.7	54.6 b	35.1 b	29.5 b
Mulch	47.0	48.6 a	108.0 a	185.5	117.5 a	75.2 a	63.5 a
Organic matter (%)							
PreHerb	4.4 a	4.9	3.5	3.3 b	3.8 b	3.2 b	4.2 bc
PostHerb	3.9 ab	4.7	3.3	2.9 b	3.2 b	3.2 b	5.6 ab
Sod	3.7 b	4.8	3.4	2.7 b	4.0 b	3.2 b	3.0 c
Mulch	4.3 ab	5.1	3.7	6.7 a	12.7 a	6.6 a	7.4 a
pH							
PreHerb	6.9	7.1	7.1	5.9	6.9 bc	6.8 bc	7.1 ab
PostHerb	6.9	7.2	7.0	5.9	7.0 ab	7.0 ab	6.9 b
Sod	7.1	7.2	7.0	5.8	6.6 c	6.6 c	6.8 b
Mulch	6.7	7.4	7.0	6.4	7.4 a	7.2 a	7.5 a

^zValues are means of three replicates. Within each year and for each variable, means followed by different letters differ at $P \leq 0.05$ by honestly significant difference test.

N/D = no data available.

compared with cover-crop treatments, and this was attributed to minimizing competition for soil water and nutrients (Glenn and Welker, 1989; Parker et al., 1993; Tworowski and Glenn, 2001). However, our long-term study did not indicate consistently better performance of trees in weed-free PreHerb plots compared with Sod despite the lack of competition with surface vegetation in the residual herbicide treatment. The year-round weed-free soil surface beneath PreHerb trees provided minimal soil organic matter inputs and gradually decreased soil macropore volume, infiltration rates, hydraulic conductivity, aggregate stability, and increased soil compaction compared with the other GMSs (Haynes, 1980; Merwin, 2003b; Oliveira and Merwin, 2001). These long-term effects of soil-active herbicides were ultimately detrimental to tree performance. Weed-free GMSs may be beneficial for tree growth and yield

during the initial years of orchard establishment. However, their negative long-term effects on edaphic conditions could ultimately limit tree productivity more than transient competition from surface vegetation during late summer and the dormant season in post-emergence herbicide and mulch GMSs, at least in humid cool-climate regions like New York (Merwin, 2003a).

By the end of this study, the Mulch had greatly increased available soil nitrate-N, phosphorus, calcium, manganese, organic matter content, and pH compared with the other GMS treatments (Table 1). Although the bark mulch was not purposely mixed into the soil, the decomposing mulch gradually formed humus that was incorporated into topsoil over the course of this study. With average bark mulch applications of 162 kg-m⁻² dry weight on an annualized basis—corresponding to inputs of 0.8 kg N/m²

annually—the total soil-N content under Mulch increased 40% from 1999 to 2006, but it subsequently began to decrease during the final years as we delayed the Mulch renewal intervals from 2 to 4 years. Research has suggested that high levels of active soil C, like in the Mulch treatment, provide a strong sink for excess N and support greater soil microbial biomass that helps to immobilize and retain N inputs in situ (Walsh et al., 1996; Yao et al., 2005). However, nitrate-N runoff and leaching from Mulch plots could become a potential problem if excess N continues to accumulate in soil under this GMS. Several studies have shown increased soil carbon content under vegetative groundcovers compared with herbicide treatments (Goulet et al., 2004; Sarno et al., 2004). However, this was not strictly the case in our study, perhaps because the soil originally had 4% soil organic matter content when treatments were established in 1992. Despite the apparent lack of long-term increases in soil organic matter under grass at this orchard, St. Laurent et al. (2008) reported higher microbial soil respiration rates under Sod compared with the PreHerb treatment and attributed that enhanced microbial activity to increased C cycling in soil under the Sod.

The effects of different GMSs on apple tree productivity did not follow continuous trends over the 16 years of this study. During the first 3 years, trees in Sod performed poorly in comparison with those in the herbicide and mulch treatments. However, during the final decade, the growth and yields of trees in Sod were not statistically different from those in the weed-free PreHerb plots. Sustained interactions of fruit trees with competing groundcover vegetation may enable those trees to adapt and compensate or avoid groundcover competition for soil water and nutrients. Furthermore, the long-term deterioration of soil physical conditions and biological activity in weed-free plots (Oliveira and Merwin, 2001; Yao et al., 2005) may eventually be more detrimental for orchard productivity than short-term groundcover competition during initial orchard establishment. Post-emergence non-residual herbicides that provide transient weed suppression during the growing season, but permit groundcover vegetation to thrive during the dormant season, may provide an optimal combination of weed suppression and soil resource conservation in orchards.

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