GROUNDCOVER MANAGEMENT SYSTEMS COMPARISONS IN APPLE AND AVOCADO ORCHARDS

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Groundcover management systems (GMSs) are essential in fruit production to achieve and sustain orchard productivity over long-term production cycles. The present dissertation compiles four studies evaluating the effects of GMSs on the long-term performance and nutrient dynamics of an apple (*Malus* x *domestica* Borkh.) orchard, and on tree growth and production, erosion rates, and root system development of a hillside avocado (*Persea americana* Mill.) orchard.

Four GMSs—pre-emergence herbicides, post-emergence herbicide, a sod cover crop, and bark mulch—were evaluated in the apple orchard. Over 16 years were no consistent long-term trends in fruit yields among GMSs, and long-term responses of trees to groundcover vegetation indicated that trees respond adaptively to compensate for surface vegetation competition. Two Nitrogen (N) budgets were developed for each GMS based on N inputs, internal cycling, and outputs, with and without applied N fertilizer. More than 60% of internal N fluxes were comprised of soil mineralization and recycling groundcover biomass; and harvested fruit represented 70% of N outputs from the system during both years. During the year with N fertilizer, N losses approached 4 and 22% through surface runoff and subsurface leaching, respectively. During the year without N fertilizer, the surface runoff N losses were twice the subsurface leaching N losses in all GMSs.

We evaluated three GMSs in a steep hillside avocado orchard in Chile—Bare soil (BS), a vegetation strip (VS), and a groundcover (GC) covering the entire surface of the plots. Three years after tree establishment, trees in the BS plots were significantly bigger and produced more fruit than trees in the VS and GC treatments, but soil physical properties had deteriorated in the BS compared to the other treatments. Runoff volumes, soil erosion, and nutrient losses were consistently higher in the BS than VS and CG treatments. Trees in BS plots had more shallow and thicker roots than in VS and GC. Lifespans of roots in the BS and VS plots were 61% and 47% greater than in the GC plots, respectively. More root production was observed in the non-bearing year than in the bearing year, in all the GMS treatments.

BIOGRAPHICAL SKETCH

The author was born in Santiago, Chile, on July 30, 1981. She studied at Pontificia Universidad Católica de Valparaíso and graduated in 2006 as an Agronomist Engineer with a Bachelors of Science in Horticultural Science. During 2005 and 2006, she worked for Sociedad Gardiazabal & Magdahl, as technical consultant and advisor. She worked closely with subtropical fruit growers of the Aconcagua Valley, conducting multiple research projects focused on technical aspects such as fertilization programs, pruning, water and soil management, pre and post-harvest diseases and pest control. During these years she gained experience and skills in several areas related to fruit crop production, and identified the need for further research in sustainable management practices, to help growers achieve long-term sustainable productions.

In 2007, the author entered the graduated program in the Department of Horticulture, Ithaca, NY, to pursue her Ph.D. under the direction of Ian Merwin, Ph.D. She received her Ph.D. in May 2012.

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CHAPTER ONE:

LONG-TERM EFFECTS OF FOUR GROUND MANAGEMENT SYSTEMS IN AN APPLE ORCHARD

1.1 Introduction

Groundcover management systems (GMSs) 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 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, turf-grasses, geotextiles and biomass mulches, and legume cover crops (Hogue and Neilsen, 1987; Merwin and Stiles, 1994; Merwin, 2003a). 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; Yao *et al.*, 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; Layne *et al.*, 1994; Klik *et al.*, 1998; 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 N.Y. 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.

1.2 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, N.Y. (Latitude – 42° 49' N, Longitude – 76° 49' W; annual mean precipitation of 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 twelve isolated subsoil drainage lysimeters. During 1991 the entire site was ploughed, 8 $MT \cdot ha^{-1}$ of dolomitic lime were 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 x 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 down-slope, 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 hrs. when droughts occurred during nine growing seasons, using micro-sprinklers that provided 32 $L \cdot hr^{-1}$ over a 4 m^2 circular area centered on each tree.

GMS 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 active ingredient (a.i.) ha^{-1}, 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^{-1} 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; 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^{-1} in mid Apr. 1992, 1993, and 1994, respectively. In May of 2005, 22.7 kg of superphosphate (0N-45P-0K) was applied as a side-dress soil application beneath all trees to evaluate N uptake and allocations after 13 yrs 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^{-1}), boron (0.6 kg B ha^{-1}), and zinc (2 kg Zn ha^{-1}) were applied annually from 2001 to 2008 at the pink or petal fall growth stages, as recommended for commercial orchards in N.Y. (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 above ground) to estimate annual and cumulative increases in tree size. Fruit yield was recorded each year from 1994 to 2008, as harvested fruit weight (kg) per tree, number of fruit per tree, average fruit size (g) and total yield per tree (harvested + dropped fruits in kg 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^{-1}) per TCSA (cm^{2}).

^{15}N tracer application and tree biomass excavation

During the year-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 $K^{15}NO_3$ (for a cumulative total of 0.5 g $K^{15}NO_3$ per tree). The amount of ^{15}N applied to each tree was kept to a minimum because our main intent was to trace allocations of ^{15}N to various parts of trees that had not received N fertilizer for the past five years, and we did not intend to estimate N-fertilizer use efficiency. In mid Apr. 2001, the dormant trees to which ^{15}N 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 (< 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 sub-sample were determined. Total N (kg tree^{-1}) and the atom-per mil ^{15}N were determined by isotope-ratio mass spectrometry at Isotope Services Lab (Los Alamos, NM). The δ^{15}N 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 mid summer with a 2-cm-diam 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 Kjeldhal digestion from 1992 to 1998, and soil C and N were determined by Dumas combustion from 1999 to 2007. Macro and micro- nutrients were extracted in Morgan’s solution (0.72 *N* NaOAc + 0.52 *N*

CH_3COOH, buffered at pH 4.8) and soil organic matter was determined by loss on ignition at 550 ^{o}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, N.C.). When significant effects were indicated within years, means were compared using Tukey's HSD 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 multi-year 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.

1.3 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 yrs for fruit production. During the establishment years (1994-2000), the Sod treatment trees were less productive than PostHerb trees (P=0.1); during the mature bearing years (2001-2008) 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 abscision in all treatments. The GMS effects on cumulative yield were more consistent throughout the years (Fig. 2). In seven of the nine yrs with significant differences among treatments, cumulative yields of trees in Sod plots were less than those of PostHerb trees.

During the first three years after planting, TCSA was greater in PostHerb than in Sod plots (Fig. 3). Begining 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 two-fold greater during the second period (2001-2008) than during the earlier timespan (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 most of those 12 yrs. In 2002 and 2005, yield efficiency was unusually low in all treatments because of weather related crop losses those years.

The above-ground dry weight biomass allocations of excavated 10-yr-old apple trees did not differ consistently among GMS treatments in 2001 (Fig. 5A). Below-ground 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 above-ground N content of excavated trees was similar among GMSs (Fig.6A). For below-ground 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 that trees in PreHerb and Sod. In contrast to total N content, in our ^{15}N tracer uptake observations, the above-ground tissue ^{15}N enrichment was greater in PreHerb trees than Sod or Mulch trees, except for trunk and scaffold biomass, (Fig. 7A). For below-ground tissues, the δ^{15}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 yrs 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 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.

1.4 Discussion

There are very few long-term reference studies of perennial fruit orchard or vineyard GMSs to compare with the results of our 16-yr 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 three to five yrs after planting, compared with weedy control treatments or mowed sod covers (Hipps *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 turf-grasses 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 Pre-Herb 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 six-yr 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 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-yr 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 following 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 five yrs. 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 (*Cyanchum nigrum* and *C. vincetoxicum*), poison ivy (*Toxicodendron radicans*), wild grape (*Vitis riparia*) and Virginia creeper (*Parthenocissus cinquefolia*). 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 (~50% surface coverage) of dandelions (*Taraxacum officinale* Weber), ground ivy (*Glecoma 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 U.S., 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 seven yrs of applying cattle manure (10 MT·ha^{-1}·yr^{-1}) and spent mushroom compost (8 MT·ha^{-1}·yr^{-1}) in a vineyard soil, compared to a control treatment without soil biomass amendments—although no significant treatment 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 vs. PreHerb tree rows (Figs. 1-4). 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 photo-assimilates and consequently reduce growth in young trees (Jordan and Jordan, 1981). Weed suppression between harvest and leaf fall reportedly increased spring tree growth the following 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 observations 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 *et al.*, 1994; Merwin, 2003a; Oliveira and Merwin, 2001).

Previous reports of N partitioning and tree-root biomass allocations in relation to GMSs were based upon 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 diam) 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 due to low soil N availability (Sanchez *et al.*, 2007; Yao *et al.*, 2005). For PreHerb, the limiting factors may be less favorable root growth conditions due to deteriorated soil physical properties (porosity, bulk density, infiltration capacity, etc.) after 15 yrs 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-reflectrometry (TDR) 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 micro-sprinklers 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 (δ^{15}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 yr-old wood, scaffold branches and main roots of trees growing in Sod (Fig. 7) compared to 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, δ^{15}N ratios in groundcover vegetations remained two to five times greater than in tree leaves (data not shown). For Mulch trees, the lower δ^{15}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 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; Tworkoski 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 N.Y. (Merwin, 2003a).

By the end of this study, the Mulch had greatly increased available soil nitrate-N, P, Ca, Mn, 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 m^{-2} 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 two to four yrs. Research has suggested that high levels of active soil carbon, as 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 where 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 carbon cycling in soil under the Sod.

The effects of different GMSs on apple tree productivity did not follow continuous trends over the 16 yrs of this study. During the first three yrs, 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.

1.5 Literature Cited

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Table 1. Long-term effects of GMSs treatments on soil nutrient availability (kg/ha), organic matter (%) and pH. Values are means of three replicates. Within each year and for each variable, means followed by different letters differ at P<0.05 by HSD test. N/D= No data available.

Variable	**1992**	**1993**	**1995**	**2000**	**2005**	**2006**	**2007**
NO^{-3}							
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
P							
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
K							
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
Ca							
PreHerb	4041.0	4733.3	2028.1	3124.8 b	3216.7 b	3620.3 b	3364.5 b
PostHerb	3192.8	4284.0	1509.0	2639.5 b	3191.3 b	3551.3 b	3060.8 b
Sod	3291.0	4107.0	1525.0	2284.8 b	3086.8 b	3276.8 b	3087.0 b
Mulch	4935.0	4700.3	1760.7	5730.7 a	12799.0 a	8248.5 a	9559.5 a
Mg							
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
Mn							
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

Table 1 (cont.)

Variable	**1992**	**1993**	**1995**	**2000**	**2005**	**2006**	**2007**
O.M.%							
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

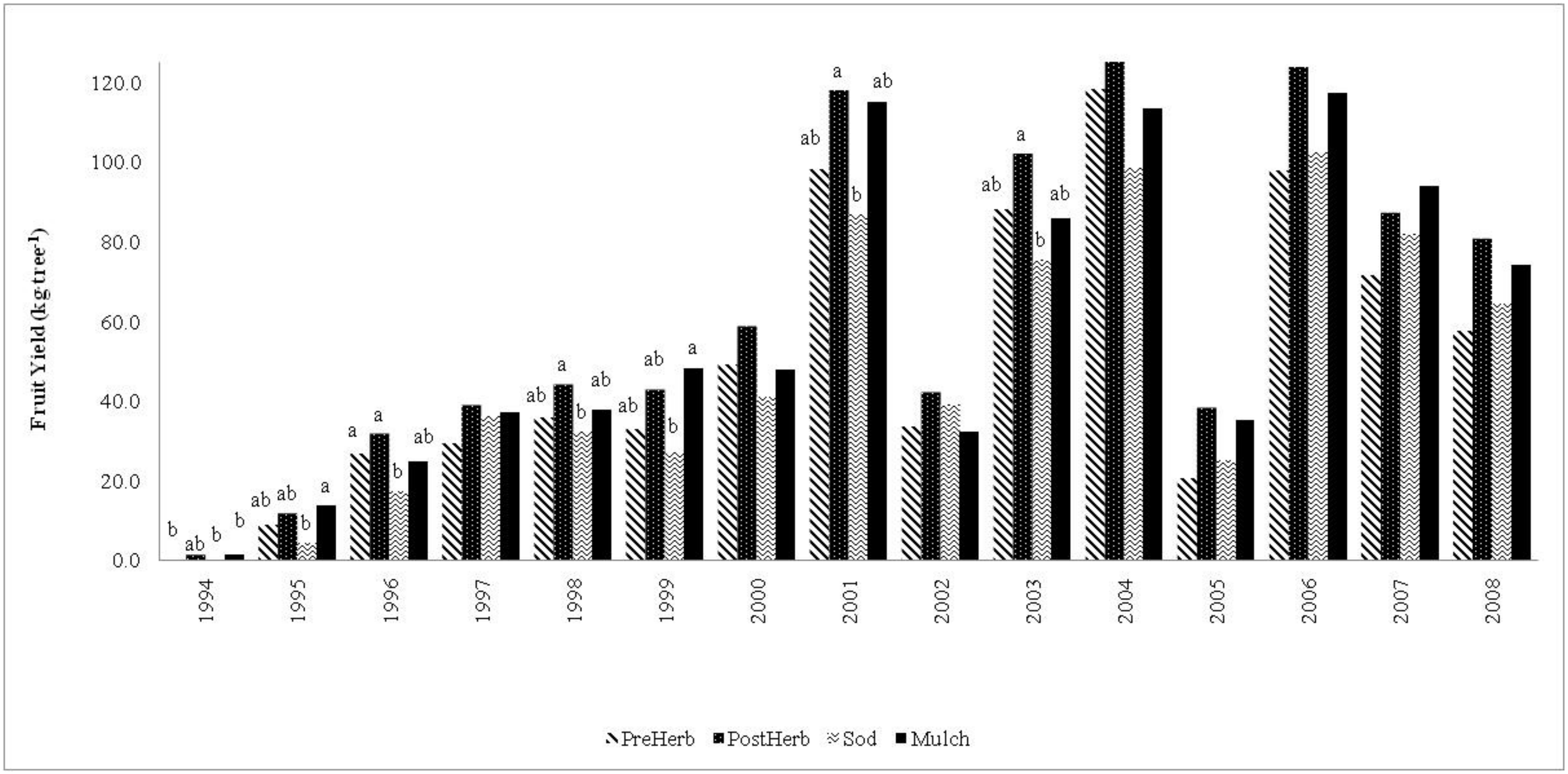


Fig. 1. Average yield (kg fruit tree $^{-1}$) from 1994 through 2008, for trees in each GMS treatment. Letters were generated from Tukey's HSD test at $P \leq 0.05$ for 1995, 1996, 1998 and 2003, and $P \leq 0.1$ for 1994, 1999 and 2001.

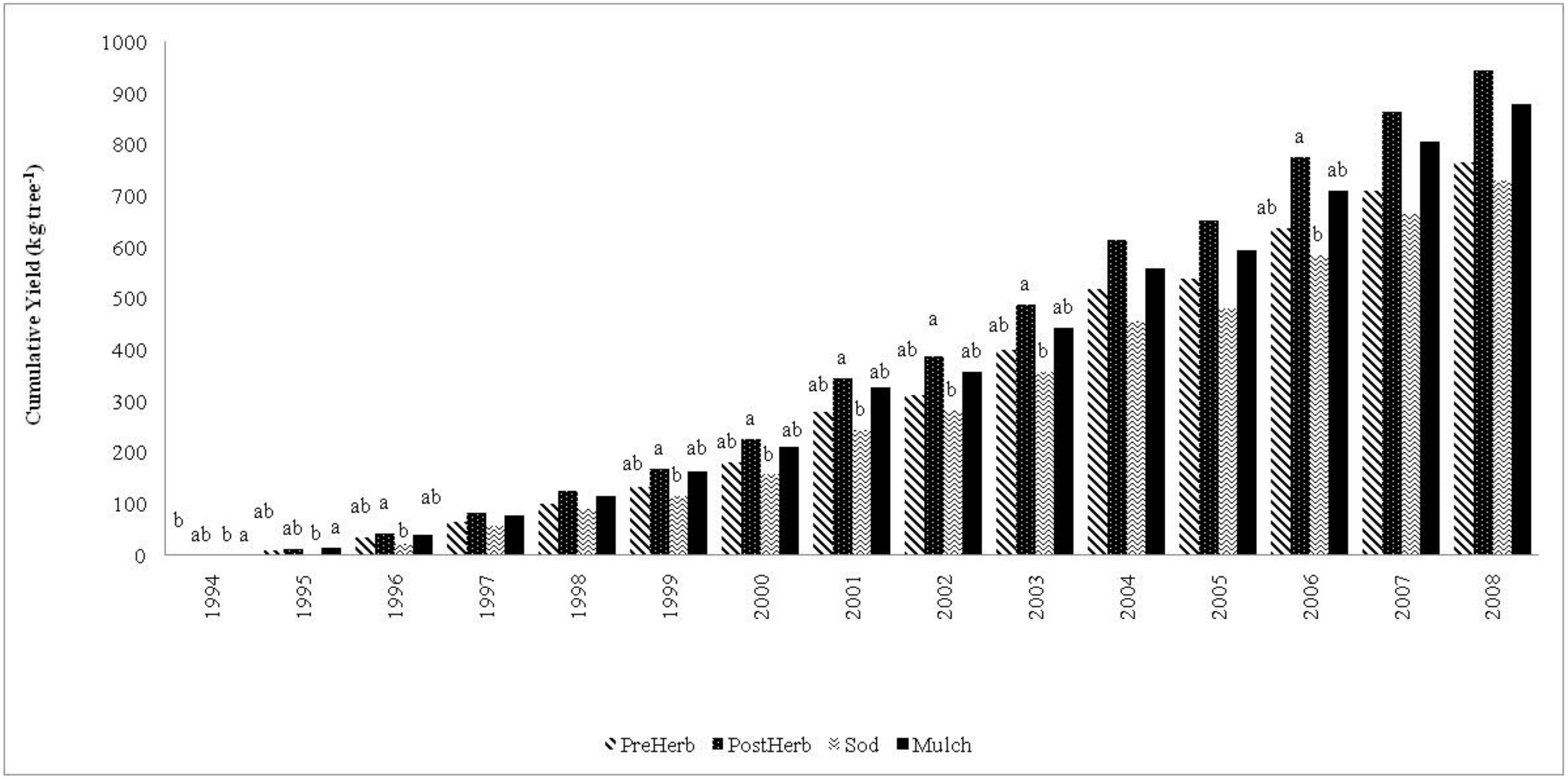


Fig. 2. Cumulative Yield (kg fruit tree^{-1}) from 1994 through 2008, for trees in each GMS treatment. Letters were generated from Tukey's HSD test at *P*≤ 0.05 for 1994, 1995, and 1996, and *P*≤ 0.1 for 1999, 2000, 2001, 20002, 2003 and 2006.

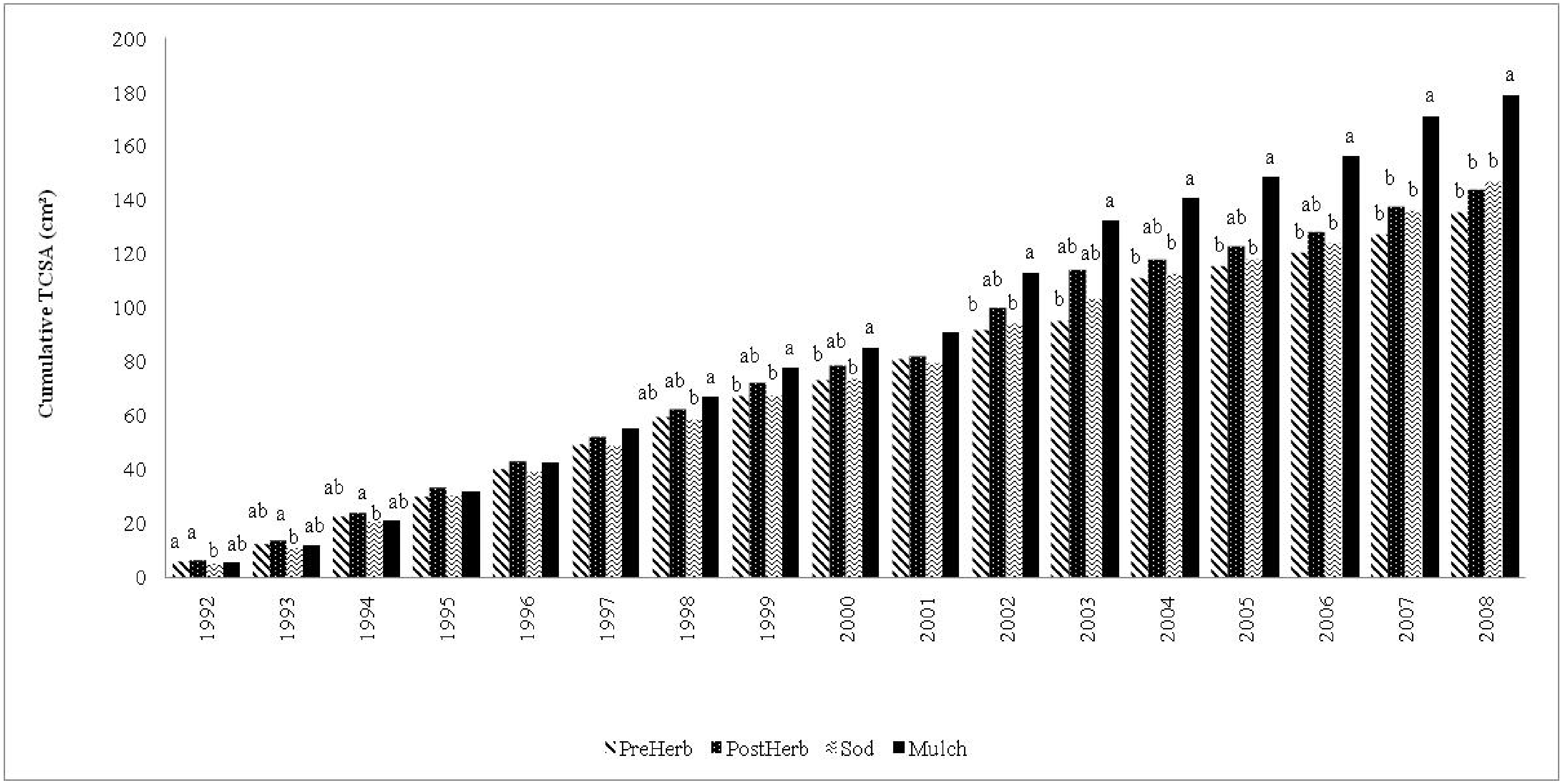


Fig. 3. Cumulative mean tree Trunk Cross Sectional Area (TCSA) (cm²) from 1993 through 2008. Letters were generated from Tukey's HSD test at *P*≤ 0.05 for 1993, 1999, 2004, 2005, 2006, 2007 and 2008, and *P*≤ 0.1 for 1992, 1994, 1998, 2000, 2002 and 2003.

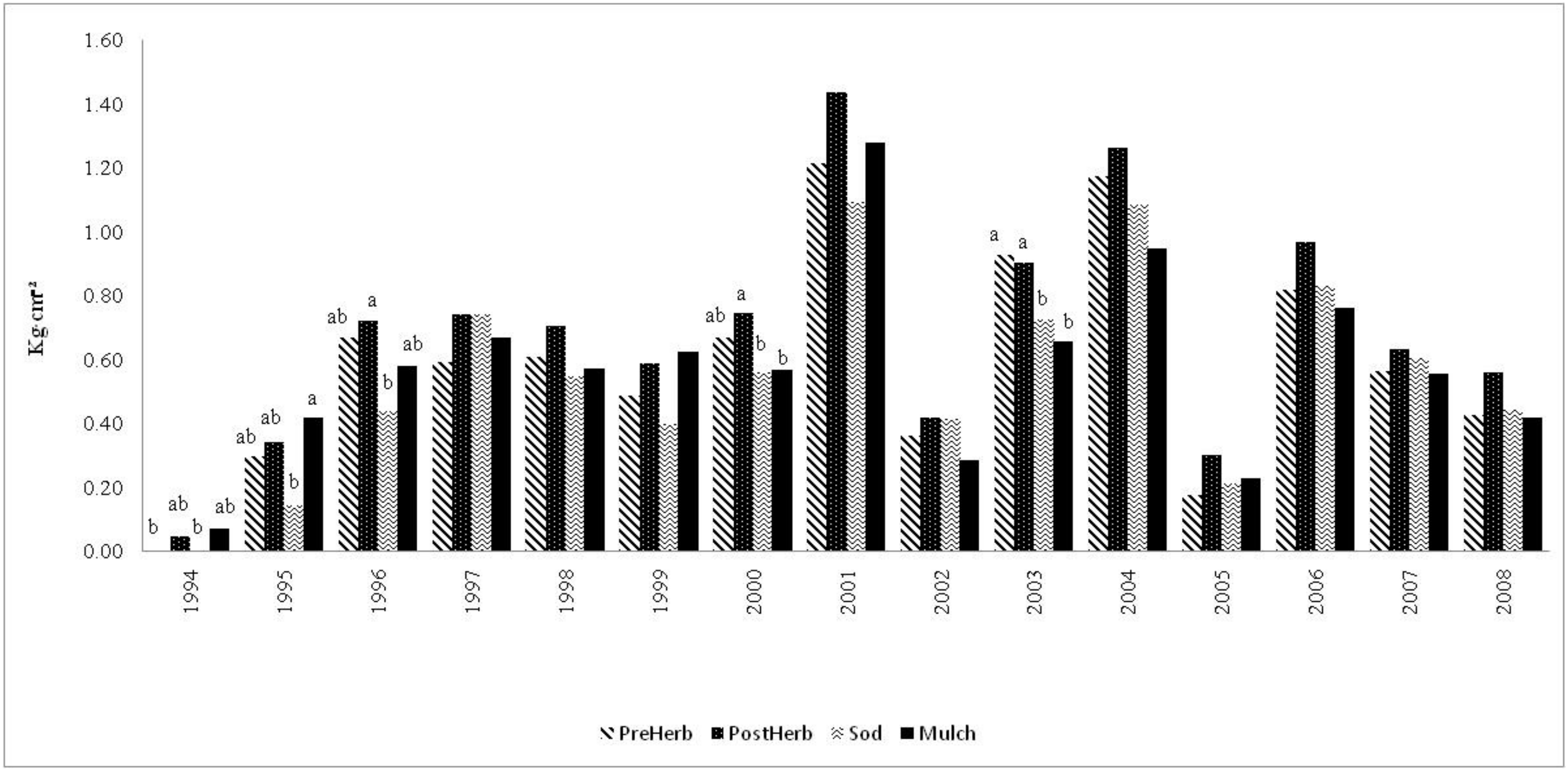
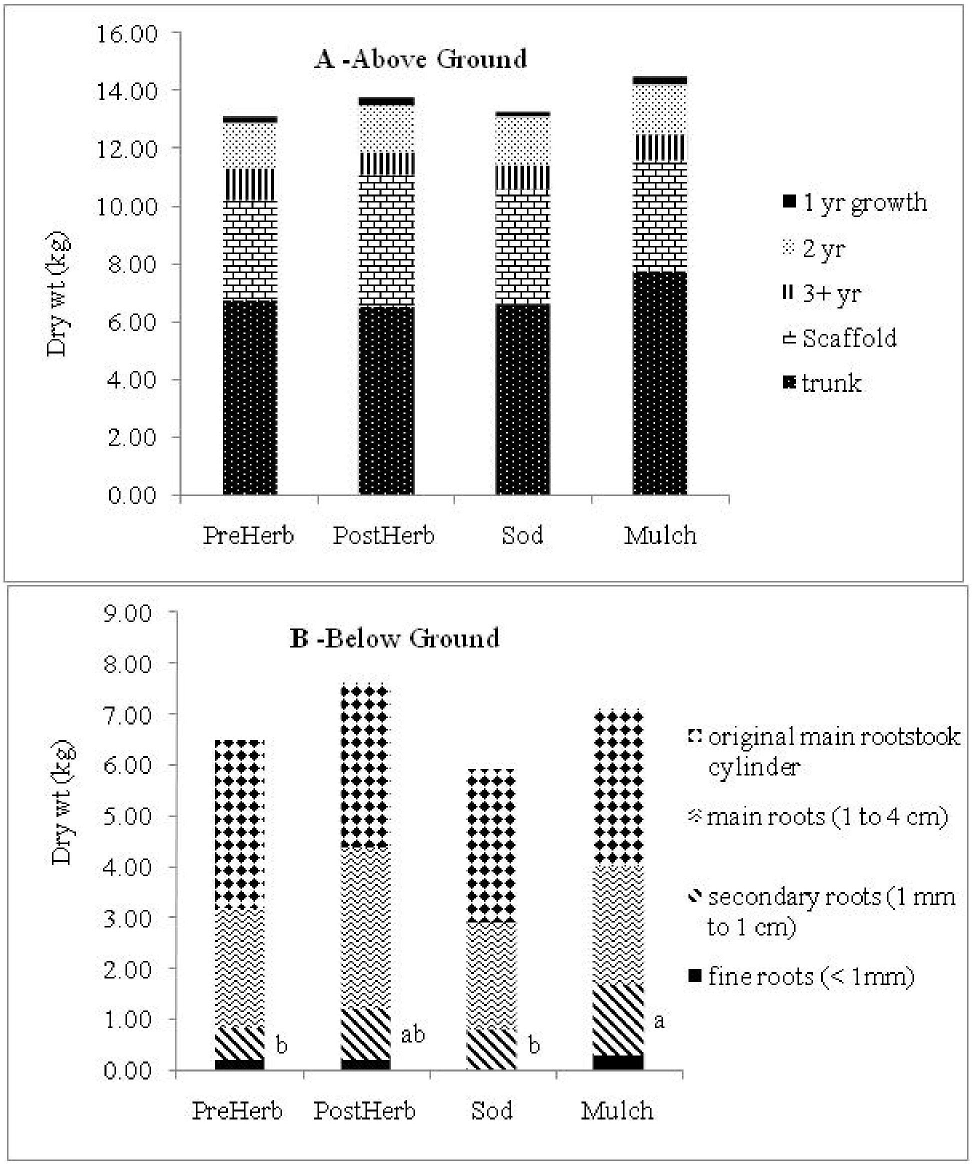
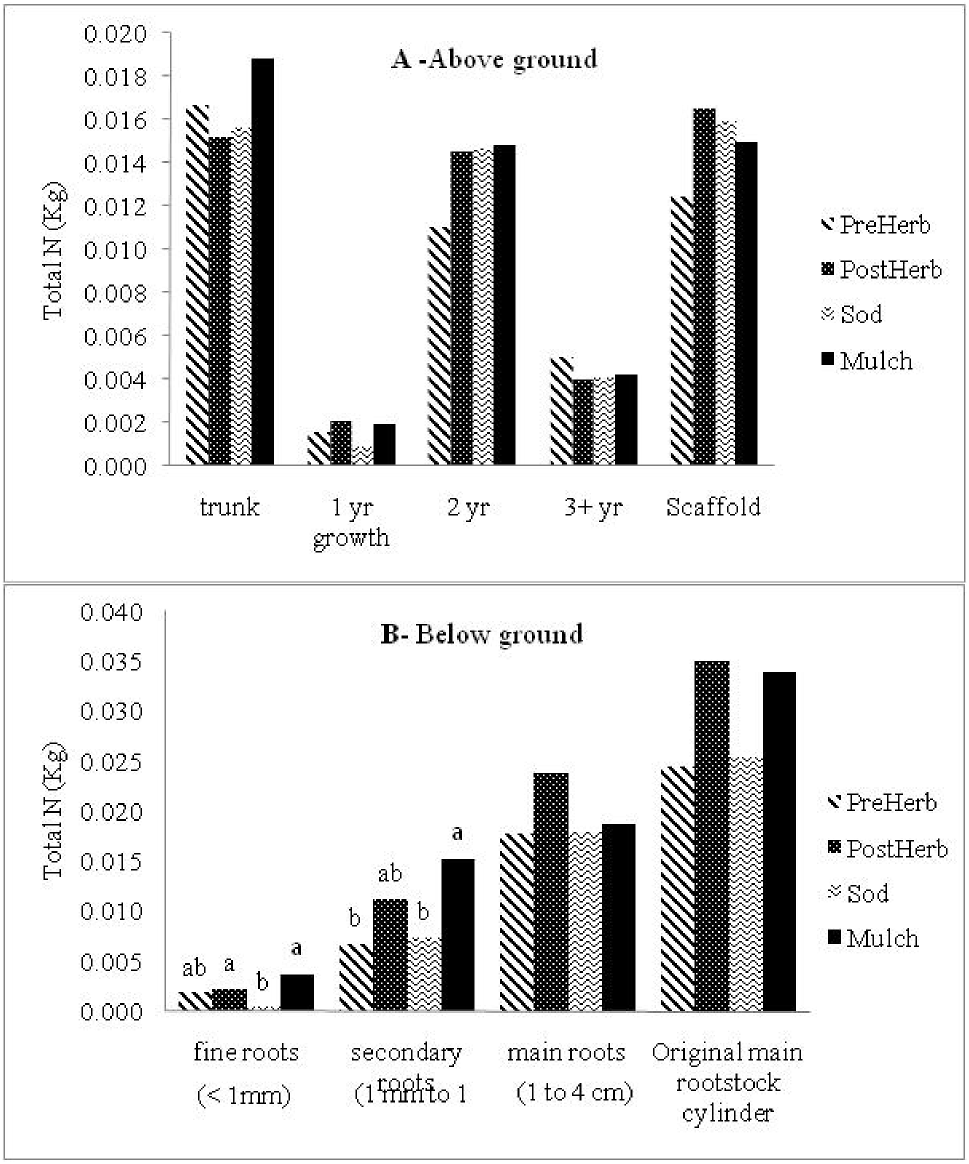


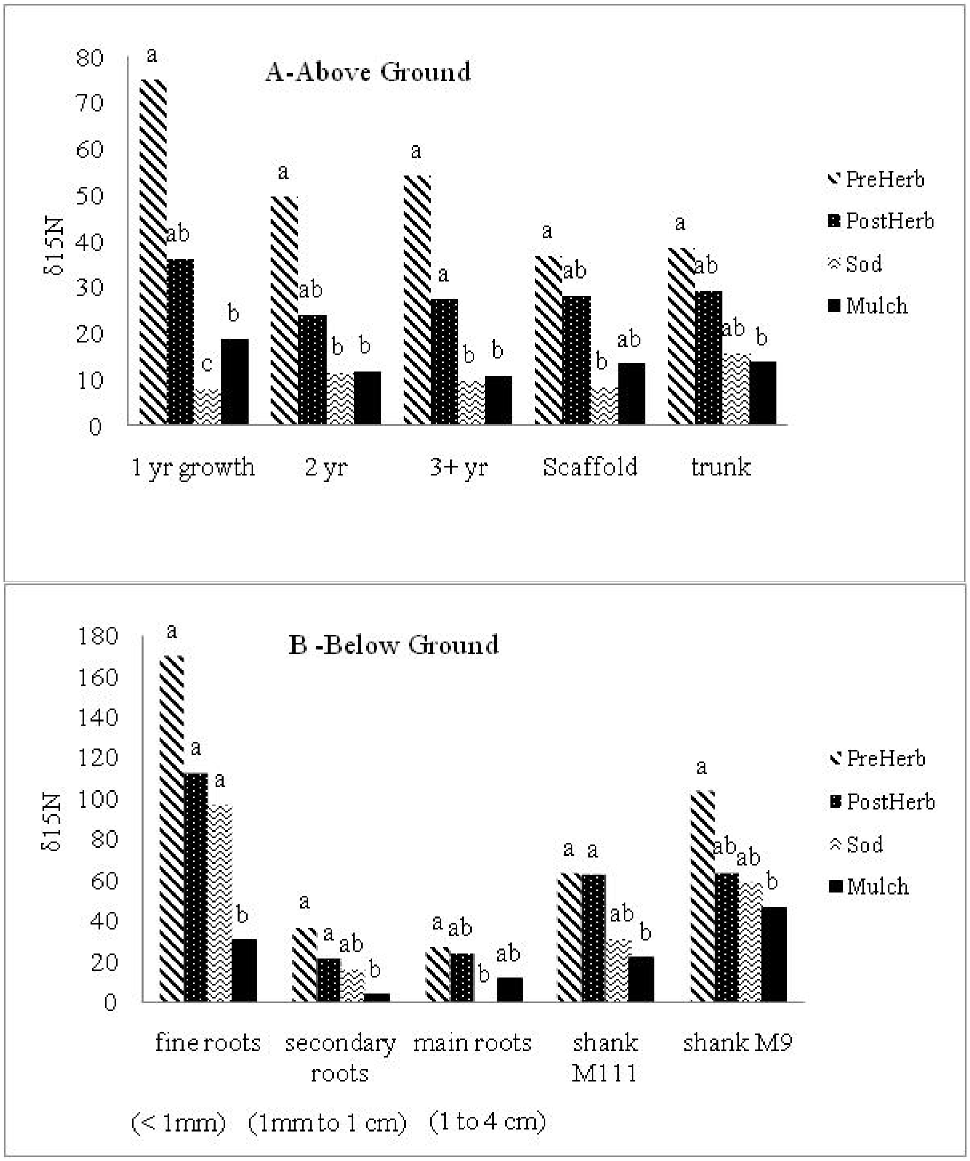
Fig. 4.Yield efficiency (kg cm^{-2}) of fruit trees from 1994 through 2008. Letters were generated from Tukey's HSD test at $P \leq 0.05$ for 1994, 1995, 1996 and 2003, and $P \leq 0.1$ for 2000.



Figs. 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 April 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 HSD test at $P \leq 0.05$.



Figs. 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 April 2001. Subsections were dried; weighed, ground, and analyzed for %N. Letters were generated from Tukey's HSD test at $P \leq 0.05$.



Figs. 7 A-B. δ ^{15}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 April 2001. Subsamples were dried, weighed, ground, and analyzed for atom. %^{15}N. Letters were generated from Tukey's HSD test at $P \leq 0.05$.

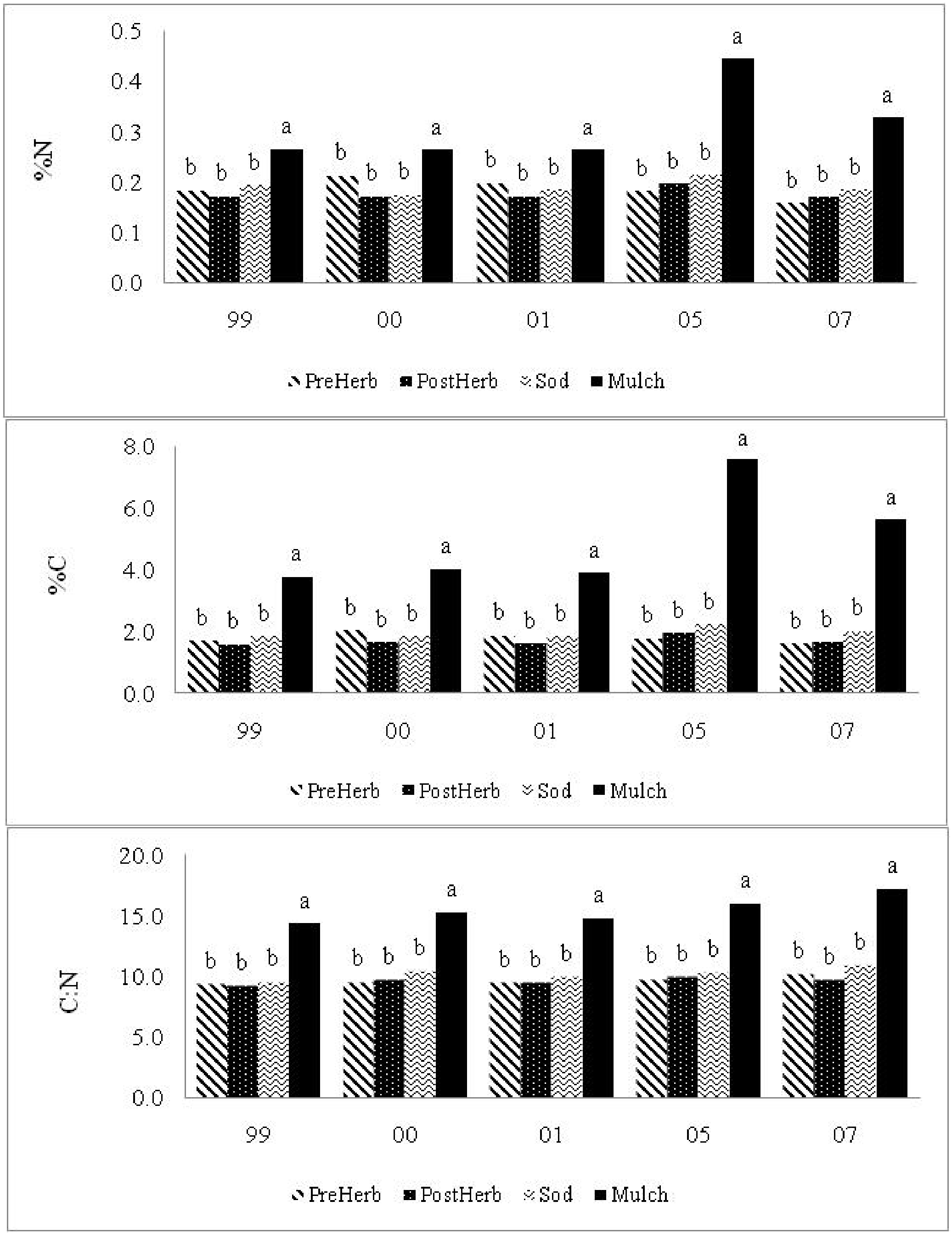


Fig. 8. The %N, %C and C-to-N ratio in soil under four GMS treatments in 1999, 2000, 2001, 2005 and 2007. Letters were generated from Tukey's HSD test at $P \leq 0.05$.

CHAPTER TWO:

NITROGEN DYNAMICS AND NUTRIENT BUDGETS IN FOUR ORCHARD GROUNDCOVER MANAGEMENT SYSTEMS

2.1 Introduction

Intensive use of pesticides and fertilizers to obtain higher crop yields has increased surface and groundwater contamination by agrochemicals, and both economic and regulatory factors are driving growers to adopt more sustainable practices. Estimating nutrient fluxes and requirements under different orchard systems is essential to produce high yields of marketable fruit while minimizing the loss of fertilizer in leaching or runoff and subsequent environmental contamination. Where nutrient inputs, recycling pools, and outputs from the crop-soil system are quantified, the retention or transfers of nutrients from one system component to another can be budgeted on a year-round basis (Haynes, 1988; Palmer and Dryden, 2006). Nutrient budgeting is a useful tool for optimizing fertilizer programs in orchards, but there are few published reports on this topic (Tagliavini et al., 1996). Over-fertilization can cause nutrient imbalances in fruit trees, and may adversely affect productivity and fruit quality. High nitrogen (N) supply during fruit ripening may depress red color development (Wargo et al., 2004), delay ripening, and induce vegetative growth late in the growing season, making trees more susceptible to winter cold damage (Haynes, 1980). Over-supply of N can also cause excessive vegetative growth that increases self-shading within the tree canopy, reducing flower bud development, fruit set, and fruit quality (Weinbaum et al., 1992).

Nitrogen fertilizer that is not taken up by plants or soil organisms is prone to leaching or runoff, and such losses are more likely when N fertilizer inputs are not adjusted for crop demand and N availability in soil (Tagliavini et al., 1996). Quantifying nutrient inputs and outputs from orchards helps to identify potential nutrient excess or shortage (Watson and Atkinson, 1999), particularly for N because it is most often limiting in orchard soils, is prone to leaching, and is often applied in relatively large quantities as fertilizer (Weinbaum et al., 1992).

Amounts of N leaching and runoff have not been extensively quantified for orchards, but reportedly vary due to differences in soil type and topography, rainfall, irrigation, fertilizer rates, mineralization and retention rates, microbial N immobilization, and soil or groundcover management (Haynes, 1988; Merwin, 2003a; Merwin et al., 1996). A seasonal pattern of nitrate-N losses through leaching has been observed in fertilized orchards, with higher N losses during times of year when rainfall exceeds evapotranspiration (Ventura et al., 2005). Annual N-leaching losses of 50 kg $N \cdot ha^{-1}$ have been reported—amounts sufficiently high to cause problems with groundwater contamination (Rossi et al., 1991).

Nitrogen removal with harvested crop biomass depends on crop yields and fruit nutrient content (Smith et al., 1988), and can range from 0.7 to 2.4 kg N per ton of fruit produced per season in apple and avocado trees, respectively (Stassen et al., 2010). Other N losses from leaf drop and prunings are reportedly minor, and may be recycled *in situ* through mowing and brush grinding (Palmer and Dryden, 2006). Nitrogen recycling through groundcover clippings is reportedly large in comparison with leaf-fall from fruit trees (Haynes, 1988). The groundcover vegetation itself takes up and retains most of the N released by its mowing, making it relatively unavailable to fruit trees, but also reducing potential N losses through leachate (Haynes and Goh, 1980b).

Internal N cycling from N reserves within deciduous fruit trees has been estimated at 45% of the total amount required for annual growth in pear (*Pyrus communis* L.) trees, and 50% for almonds (*Prunus amygdalus* L.) (Millard, 1995). Because of the relatively high contributions from internal cycling to total N requirements, many deciduous orchards show little response to N fertilizer applications. In the absence of competition from weeds, mineralization of soil organic matter and atmospheric deposition may provide enough N for established fruit trees (Greenham, 1980; Stiles and Reid, 1991).

Although there is little published information in this regard, nutrient availability, recycling and losses probably vary among different orchard groundcover management systems (GMSs) (Merwin et al., 1994; Merwin and Stiles, 1994; Merwin et al., 1996). N-mineralization is greater in soil environments favorable to this microbial process, which releases plant available N forms from soil organic matter (Haynes, 1980). Soil organic matter (SOM) content is generally higher in GMSs that include mulches, year-round groundcover or surface vegetation during part of the year (Hogue and Neilsen, 1987; Merwin, 2003a). SOM promotes N mineralization by increasing soil microbial biomass and activity (Yao et al., 2005), ultimately releasing nutrients to tree roots (Hogue and Neilsen, 1987). The N recycling in soils under clean cultivation or continuous use of soil-active herbicides is reportedly lower than that under groundcovers, because of decreased return and incorporation of plant residues to the soil in weed-free orchards, compared with GMSs such as mulches and mowed grass covers (Hogue and Neilsen, 1987; Merwin, 2003b).

Differences in nutrient budgets would be expected among orchard GMSs because nutrient inputs, and presumably outputs, differ among the various systems. These differences could be important for fertilization programs, and should be considered to avoid over-fertilization. Despite the established relationship between soil nutrient availability and groundcover or soil management, there have been few long-term studies measuring the impact of GMSs on orchard nutrient budgets. The present study was intended to compare the impacts of GMSs and N or P fertilization on nutrient retention and fluxes in an apple orchard. Our objective was to quantify the major inputs and outputs of N in an orchard after many years under four different GMSs, with and without N and P fertilizer applications. The main hypotheses of this experiment were: 1) The four GMSs would cause different amounts of leaching and runoff, with different concentrations and effluxes of N and P in the experimental orchard; 2) surface vegetation and soil moisture content differences among the four GMSs would lead to different decomposition and N mineralization amounts; 3) different tree growth and crop yield patterns among the GMSs—interacting with the soil and hydraulic processes described in the first two hypotheses above—would lead to different optimal N budgets for trees in each GMS.

2.2 Material and Methods

Experimental site.

The experimental site was a 0.8 ha, 17-year-old orchard located on the east side of Cayuga Lake near Ithaca, N.Y. (Latitude – 42° 49' N, Longitude – 76° 49' W; annual mean precipitation of 76 cm). The soil at this site is an Ovid glacial till, silty clay loam (mixed mesic Glosaquic Hapludalf), that was prepared for planting in 1991 by removing a previous old apple orchard and installing a replicated subsoil grid of 12 drainage lysimeters. After the site was limed, ploughed and cultivated thoroughly, red fescue (*Festuca rubra*) turf grass was sown in May 1991 throughout the area to be planted. Apple trees ('Empire' on 'M.9'/'MM.111' interstem rootstocks) were planted in April 1992 at 3 x 6 m spacing. Four GMS treatments were established in 2-m-wide strips within the tree rows, and have been maintained since 1992. These GMS treatments were assigned randomly to 12 plots in April 1992, with three replicates of each treatment. Each experimental plot was 9-m wide across the slope and 25-m long down-slope, including four parallel tree rows containing 20 to 24 trees each, and separated by 4-m wide turf grass drive lanes (Merwin et al., 1996).

GMS treatments.

The four GMS treatments were: 1) PreHerb: A pre-emergence residual herbicide treatment consisting of three herbicides (glyphosate, norflurazon and diuron) tank-mixed at 2.0, 3.0 and 2.5 kg a.i.·ha^{-1}, respectively, applied in mid-May each year; 2) PostHerb: A post-emergence herbicide treatment consisting of glyphosate applied at a rate of 2 kg a.i. ha^{-1} in mid-May and July each year; 3) Mowed Sod: A red fescue (*Festuca rubra* L) turf grass originally seeded in 1991, that eventually comprised a mixture of various grass and broadleaf species, mowed monthly during the growing season each year; 4) Mulch:

A 15-cm thick layer of partially composted (4 to 6 months of thermo-composting before applications) shredded hardwood bark mulch (a mixture of *Acer*, *Quercus*, *Juglans*, *Fraxinus*, and *Tilia* sp.), applied in 1992, 1995, 1998, 2000, 2002 and 2005. Mulch was applied at a rate of 27 kg·m^{-2} and the N content (dry weight) of the bark mulch material averaged 0.47%. Glyphosate herbicide was spot-applied to the Mulch plots in mid-May annually from 1996 onward, to suppress emergent perennial weeds (Oliveira and Merwin, 2001; Yao et al., 2005).

Orchard Management.

Soil and tree nutrient content have been analyzed annually since 1992, and for the present study we monitored nutrient dynamics in a year with N and P fertilizer additions (2005), and another year without ground-applied fertilizers (2007). Trees were fertilized in May 2005, applying ammonium nitrate (34N-0P-0K) at a rate of 318 g·tree^{-1} equivalent to 0.108 kg N·tree^{-1} and 60 kg N·ha^{-1} —a typical N amount for apple trees of this age and size in commercial N.Y. orchards. Routine fertilizer P applications for mature apple trees are not recommended in N.Y. orchards (Stiles and Reid, 1991), but to test for differential GMS effects on P leaching, we applied 22.7 kg of superphosphate (0N-45P-0K) as a side dress soil application beneath trees in May of 2005. During the following years (2006, 2007 and 2008) no N or P fertilizers were applied beneath trees in this study.

Subsurface drainage and surface runoff sampling system.

In 1991, a subsoil drainage system with a replicated grid of perforated polyvinyl chloride (PVC) drainage lines was installed beneath the experimental plots. These 12 independent subsurface drainage lines intercepted leachate from four contiguous tree rows that comprised each GMS treatment replicate. All the plots were hydrologically isolated from each other by installing perimeter drainage interception lines at 0.8 m depth in 6-m-wide surrounding buffer zones. A single perforated PVC line was installed at 0.7-m depth down the center of each GMS plot, draining to the down-slope edge of each treatment area, and then coupled through solid (non-perforated) PVC pipes to a belowground collection station where subsurface leachate from individual plots was collected for analyses. The approximate drainage interception area for each sampling station was 48 m^2; representing a 2-m-wide swath lengthwise above the subsoil drainage line transecting each GMS plot.

Surface runoff was measured with tipping buckets at the lower edge of a 6-m^2 area within one tree row of each GMS plot. A micro-sprinkler irrigation system, capable of delivering 32 L hr^{-1} of water over the GMS treatment area beneath each tree, provided irrigation and facilitated water sample collection when there were prolonged dry periods. To collect water samples for chemical analyses, a 2-mm-diameter hole was bored above a small dam in each drainage outfall pipe to divert some out-flowing water into sample bottles suspended beneath the collection pipe. For each outflow collection site, a tipping bucket was attached with a battery operated Hobo-8 data logger (Onset Technologies, Bourne, Mass.) to record the number of tips. These calibrated tipping buckets measured continuous outflow of water from each plot in both subsurface drainage and surface runoff systems: multiplying the number of tips with the calibrated value of each tipping bucket to estimate total outflows (Brown, 2005). Water flow in subsurface leaching and surface runoff was measured from Mar. to Nov. 2005 during the first (fertilized) phase of this study, and from May 2007 to Apr. 2008 during the second (unfertilized) phase. Nutrient concentrations in subsurface leachate and surface runoff were measured periodically (whenever the sample bottles were full) during those same two observation periods.

Nutrient budgets were constructed using the entire datasets from both years of the study. For comparing mean values in 2005 vs. 2007, the flow volumes and N and P concentrations in water samples were calculated and compared for equivalent time periods each year. Estimated N and P losses per hectare were calculated based on the data for each year, adjusted because each GMS treatment area represented one third of the total orchard floor area (only the tree rows) while the other two thirds was covered with turf-grass drive lanes that were the same for all GMSs throughout the site.

Fruit yield and nutrient analyses.

Fruit yield was recorded from 1994 onward, as harvested fruit (kg) per tree, fruit counts, fruit size (g), and total yield per tree (harvested + dropped fruit in $kg \cdot tree^{-1}$). Fruit yield data were collected separately for each tree and then averaged to provide a treatment mean for each GMS replicate. During harvest in 2005 and 2007, a random sample of 10 apples per plot was selected for total N analysis. Two slices from opposite sides of each fruit were oven dried at 70° C over several days to constant weight, and sent to the Cornell Nutrient Analysis Laboratory (CNAL, Ithaca, N.Y.) to determine C and N content by Dumas combustion. To calculate total N exported in fruit, the average yield for each study year was multiplied by the percentage of N and total amount of fruit harvested that year within each plot, and extrapolated to one hectare (555 trees).

Total N in leaf biomass and pruned wood.

To determine the amount of N recycling from leaf drop, one representative tree in each plot was completely wrapped with nylon netting in early autumn to catch all of its leaves as they abscised. When leaf drop was complete, leaves were collected and oven-dried to constant weight at 70°C over several days. Dry weights of these samples were recorded, and then multiplied by N leaf content (measured as mentioned above for fruit samples) for 2005 and 2007 respectively. During the Winters of 2001 and 2009, all of the wood trimmings were collected after pruning two trees in each plot, oven-dried to constant weight, and analyzed for total N by Dumas combustion. Values of total N recycling from pruned wood during 2001 were used to estimate N budgets for 2005, and values from 2009 were used to estimate N budgets for 2007 each GMS.

Litter collection and litter bag preparation for residue decomposition study.

During the 2005 and 2007 growing seasons, a litter decomposition study was carried out using chopped surface vegetation from each GMS and placing it into nylon mesh bags. The initial litter samples were collected on June 2005 and May 2007, from a randomly selected 1-m^2 area within the 2-m wide

GMS treatment strip of each plot. A quadrangle frame (1-m^2) was thrown into the 2-m wide treatment strips at randomly selected sites, and the aboveground biomass of surface vegetation within each sample-quadrant was severed at the soil surface and collected in paper bags.

From each plot, an average of 1.0 kg fresh weight of litter sample was collected, taken to the lab, and oven dried at 70°C over several days to constant dry weight. In 2005, three nylon mesh bags of 24 x 24 cm (2-mm mesh) were used for each plot, with an initial 50 g of oven-dried litter sample in each mesh bag. In 2007, groundcover litter samples were sorted into four categories: apple leaves, grasses, legumes, and other broadleaf species. Five nylon mesh bags of 20 x 40 cm dimension were used for each plot as replicates over time, with an initial 40 g of oven-dried litter sample in each mesh bag. For sequential sampling, each treatment replicate had a set of five bags containing a representative proportion of apple leaves, legumes, grasses, and broadleaf species collected from the respective plots.

For both years of this study, before the field decomposition tests, one litter bag per plot was measured for total C and N by Dumas combustion (C-to-N of initial litter samples). To estimate decomposition and N mineralization rates in the orchard, the litter sample mesh bags were placed midpoint between trees within each plot in the tree row. Soil surface vegetation was removed at the mesh-bag placement site to allow contact of the mesh bags with the soil at each decomposition site. To keep mesh litter bags in place, a black plastic screen was placed over them and pinned to the soil surface at each corner.

One bag from each plot was removed without disturbing the surrounding bags, at monthly intervals from Aug. to Oct. 2005, and at six-week intervals from June to Oct. 2007. After each removal, the litter sample remnants were placed into paper bags so that no material was lost during transportation to the laboratory for processing. The litter samples were then weighed to obtain fresh weights, and oven-dried to a constant weight at 70°C over several days. Dry weights of the samples were recorded, and total C and N content of the remaining litter residues was measured by Dumas combustion. Based on C-to-N ratios and dry weight of the remaining litter mass at three removal dates, we calculated the percentage of decomposed litter mass at each removal date, N-mineralization rate, and quantity of N released per kg of litter from each GMS treatment.

The percentage of the initial litter mass remaining (*PLR*) was calculated as litter biomass remaining at each removal date, based on the initial litter mass recorded at the start of the study using the following equation:

$$\text{PLR} = [(\text{Initial Wt} - \text{Final Wt}) / \text{Initial Wt}] \times 100 \qquad \text{Eq.[1]}$$

For calculating N-mineralization rate, first we calculated the difference in dry weight for the three removal times:

$$\Delta \text{ wt} = (\text{Initial Wt} - \text{Final Wt}) / \text{Incubation day} \qquad \text{Eq.[2]}$$

This was denoted as Δ wt ($g \cdot d^{-1}$). To calculate an approximate %N present in litter between each removal, we averaged %N content of the litter sample (initial and final). The value obtained was denoted as n (% N):

$$n = (\%\text{ N-Initial} + \%\text{ N-Final}) / 2 \qquad \text{Eq.[3]}$$

Using equations [2] and [3], the N-mineralization rate was calculated as:

$$\text{N-mineralization rate } (g \cdot d^{-1}) = \Delta \text{ wt} \times n \qquad \text{Eq.[4]}$$

The amount of N released per kg of surface vegetation biomass was calculated in two steps; first the grams of N remaining in litter bags after each removal were calculated by multiplying dry weight of litter and %N content at each removal date.

$$\text{Grams of N remaining} = \text{Final Wt} \times \%\text{N} \qquad \text{Eq.[5]}$$

Grams of N released per bag over time were calculated by subtracting the grams of N remaining after each removal day from the initial N content of the samples.

$$\text{N released (g) per bag} = \text{Initial g N} - \text{g N at removal dates} \qquad \text{Eq.[6]}$$

Grams of N released per mesh bag over time were converted to g of N released per kg of surface vegetation biomass using a conversion factor x/a (where x is the grams of N released per sample, a is the dry weight of the initial sample), and the resultant value was multiplied by 1,000 g to convert it to $g \cdot kg^{-1}$:

$$\text{N released per surface vegetation } (g \cdot kg^{-1}) = x/a\ (1000) \qquad \text{Eq.[7]}$$

A regression model was fitted for each GMS treatment to predict the release of N over time from groundcover vegetation. Time (in days) and N released per unit of surface vegetation ($g \cdot kg^{-1}$) were the two parameters of this model.

Groundcover biomass estimation.

To estimate surface groundcover biomass ($kg \cdot ha^{-1}$) production under different GMSs, tree-row surface vegetation samples were collected in June 2005, and May and Aug. 2007, from the 2-m wide strips of each GMS treatment, using 1-m^2 quadrangle frames thrown within the tree rows at random sites to collect a representative sample. The groundcover biomass samples were taken to the laboratory and oven-dried at 70° C to constant weight. Dry weights were recorded and converted into $kg \cdot ha^{-1}$, using a conversion factor x/a [where, x is biomass dry weight recorded from samples for each plot, a is litter sample collection area of that plot (1.0 m^2)], and the resultant value was multiplied by 10,000 m^2 to convert it to kg biomass production ha^{-1}:

$$\text{Biomass production } (kg \cdot ha^{-1}) = x/a\ (10000) \qquad \text{Eq. [8]}$$

Using the regression equations obtained for N release over time in the mesh litter-bag experiment, we estimated the total N released from groundcover biomass in each GMS during each growing season.

Data-logging soil moisture and temperature.

Soil temperature and moisture monitoring probes were installed in each plot for continuous data-logging. Soil temperatures at 5 and 25-cm depth in soil were recorded using Campbell Scientific Water/Soil Temperature probes (P/N 107-L), rated for –35° to +50° C. From 1994 to 2007, soil volumetric moisture content was recorded using CS-615 Time Domain Reflectometry (TDR) probes (Campbell Scientific, Logan, Utah). During the Summer of 2007, the original soil moisture probes were replaced with ECHO20 TDR units (Decagon Devices, Wash.) placed in the same location as the previous TDR probes. A multiplexer (CSI P/N AM 416) was used to distribute data from the 12 soil moisture probes and 24 soil temperature sensors to a Campbell data logger (CR10X) enabling us to record data at hourly intervals continuously year-round from all sensor probes in the 12 GMS plots (Brown, 2005).

Volumetric soil water content data were averaged weekly for each plot to facilitate interpretation and comparison of these two yearly data sets for practical purposes. When soil-monitoring data were missing due to technical problems (e.g. lightning strikes at the site during one summer), we estimated missing values by extrapolating from averages of comparable time intervals for other plots at the site.

Soil N mineralization.

Soil N mineralization rates under different GMS treatments were estimated on the basis of potentially mineralizable nitrogen (PMN), corrected for soil temperature and moisture as suggested by Hadas et al. (1989). The PMN values were obtained from a laboratory incubation experiment with soil samples from the 12 plots (Leinfelder, 2010). The N mineralization (Nt) was estimated on a weekly basis, using the first order rate equation suggested by Stanford and Smith (1972):

$$Nt = N_0 (1- e^{-kt}) \qquad \text{Eq. [9]}$$

where N_0 is the potentially mineralizable N pool and k is the rate constant. According to Stanford and Smith (1972), the relationship between soil N mineralization and soil temperature is explained by the following equation:

$$k = 10^{(7.71-2758/ (273 + T))} \qquad \text{Eq. [10]}$$

where k is the exponential rate constant in Equation [9] in weekly units. Weekly mean temperatures were obtained from the average recorded soil temperatures at 5 and 25 cm depth. Temperatures below 25 cm were assumed to be similar to those at the 5 to 25-cm depth.

According to Stanford and Epstein (1974), Nt can be corrected for variable soil moisture conditions in the field by the following equation:

$$N_{w/c} = Nt \times WC/WC_{opt} \qquad \text{Eq. [11]}$$

where $N_{w/c}$ is the amount of N mineralized under field soil-moisture content (WC) and WC_{opt} is the moisture content at field capacity. Based on our previous observations of soil water content at this site, we assigned a value of 0.4 $g \cdot g^{-1}$ to WC_{opt} (Oliveira and Merwin, 2001) and assumed it was relatively constant over the rooting depth interval of apple trees.

Water analysis for nutrient concentrations.

After precipitation or irrigation events, water samples were collected in HDPE Nalgene bottles, from access stations in subsurface drainage and surface runoff sampling stations. Samples were filtered through Whatman Glass Microfibre Filter paper (Fisher Scientific, N.H.) and frozen at -20°C for subsequent analyses of N and P concentrations to be run by continuous-flow colorimetry (Perstorp Analytical, Alpkem, Ore.). Nitrate-N was run on an automated cadmium reduction method to measure nitrate plus nitrite-N. Tests of sample subsets showed that nitrite-N was negligible, and for the purpose of this report we assumed that nitrate-N ($N0_3$-N) was the predominant N form present in our water samples. Orthophosphate (PO_4-P) was run on automated ascorbic acid method (Clesceri et al., 1998).

Soil analysis.

In Oct. 2005, soil samples were collected with a trowel from 30-cm deep holes beneath the tree canopy of four nested replicate rows within each plot. In Aug. 2007, 12 samples per plot were collected with a 2-cm-diam metal core at 0-20 cm depth. Samples were analyzed for nutrient content by Dumas combustion (for C and N), inductively coupled argon plasma spectroscopy (for other macro and micronutrients), and pH and organic matter (by loss on ignition) at the CNAL facility.

Nitrogen budget.

A balance sheet of nutrient inputs and outputs for each GMS treatment was prepared, following a general conceptual model reported by other researchers (Di and Cameron, 2000; Goh and Haynes, 1983; Haynes and Goh, 1980a; Nguyen et al., 1995; Watson and Atkinson, 1999). Fertilizer applications and N inputs from irrigation, precipitation and mulch were tabulated as external N inputs to the orchard. The N releases from aboveground biomass decomposition, litter fall and pruned wood, and soil mineralization were tabulated as internal fluxes; and N losses through harvested fruits, surface runoff and subsurface leaching were tabulated as outputs from the orchard. Biological N fixation, atmospheric particulate N deposition, N immobilization in soil, denitrification or ammonia volatization from soil, and N diffusion from tree canopies were not assessed in our study.

During 2005, water flow data were recorded from May to December, and samples to estimate NO_3-N and PO_4-P concentrations in water flow were taken from June to November. Data from a decade of previous observations at this site for N concentrations and flow volumes were used to estimate nutrient losses during Jan., Feb., Mar., Apr., May and Dec. 2005. A subset of surface runoff and subsurface leaching samples were analyzed for total N content in all forms, and a correction factor was calculated to estimate total N losses through surface and subsurface water in the final N budget.

The N loss in harvested fruits from the orchard in 2005 was estimated using an average fruit yield per GMS from 2000 to 2005, because in 2005—due to unusually hot weather during June after chemical thinning sprays—fruit yields were abnormally low in all the treatments. To estimate the N mineralization from mulch biomass, we assumed that each bark mulch application would take five years to decompose and release its total N content, and calculated its yearly N input as 20% of its total N content. Mulch was applied in 1992, 1995, 1998, 2000, 2002 and 2005 at a rate of 27 kg of dry mulch per m^2 with an average dry weight N content of 0.47%. All calculations for constructing N budgets reflected the fact that the GMS treatments covered 1/3 of a hectare (only tree rows) while the other 2/3 of the site were covered with the same turf-grass drive lanes in all treatments.

Precipitation and irrigation water.

Precipitation was recorded throughout the study at an automated weather station nearby in the same orchard. During the Summer of 2005, trees were irrigated once in May after the ground fertilizer applications, and several times during June and July. During the Summer of 2007, trees were irrigated only twice, during June. The N and P concentrations in irrigation water were obtained for 2005 and 2007 from regional monitoring reports for Cayuga Lake (the source of irrigation water at this site); for precipitation N and P content, data were obtained from the National Atmospheric Deposition Project (NADP/AIRMoN) monitoring location NY67, in nearby Ithaca N.Y.

Data analysis.

Soil and fruit nutrient analyses, tree growth and yield, and total leaf and groundcover biomass were analyzed as a one-way analysis of variance model (JMP, Version 7. SAS Institute Inc., Cary, N.C., U.S.). A repeated measures model was used to analyze water flow and nutrient losses within years, and only data recorded for the same period of time in both years were compared for statistical analyses. The N budget table was elaborated with the entire sets of data recorded in both years.

2.3 Results

Total groundcover biomass was greatest in Sod plots during 2005 and 2007; Sod had almost twice the groundcover biomass in other treatments during 2005, and three times more biomass than other treatments in 2007 (Table 1). There was sparse groundcover biomass in the two herbicide and the bark mulch plots during the early May sampling times each year, due to dormant season growth of groundcover vegetation in these three GMSs.

No differences in number or dry weight biomass of leaves or pruned wood per tree were observed among the GMS treatments (data not presented).

Trends in soil water content during 2005 and 2007 were complex and varied between the two years, as well as among treatments during each growing season (Fig. 1). Soil water content under Sod was greater than other treatments in the first part of 2005. The PreHerb plots were drier than the other GMSs during most of 2005, which was an unusually warm and dry growing season from May to Sept. During 2007, the Sod plots had greater soil moisture during the spring and summer months, in comparison with other GMS plots. The PreHerb plots had the lowest soil water content values for most of the year-2007 growing season.

The estimated rate of N release from groundcover residues in litter decomposition simulations was highest for the Mulch treatment in both years (Fig. 2), and higher in all GMSs during 2005 compared with 2007. On a per-gram-biomass basis, there were no significant differences among the GMSs for N release from groundcover residues in 2005; but in 2007 the Mulch plot groundcover litter released more N than the other treatments. When litter N release was regressed on the initial C-to-N ratios of groundcover residues in each GMS during 2005, there was a significant negative trend for N release as the C-to-N ratio of groundcover residues increased (Fig. 3). In contrast, during 2007 when N fertilizer was not applied beneath the trees, the C-to-N ratios for groundcover biomass were higher, and the amount of N released from litter decomposition was lower than in 2005.

Soil total C, N, and C-to-N ratios—data are presented in chapter 1.

Soil mineralization rates under different GMSs, estimated as potentially mineralizable nitrogen (PMN) and corrected for soil temperature and moisture, differed greatly among the four treatments. The PMN per ha of soil to 0.5-m depth followed similar trends in both years (Fig. 4). The treatment rankings for PMN rates were Mulch > Sod > PostHerb > PreHerb; and the N mineralization rate of PreHerb soil was only 10% that of Mulch soil.

The N inputs from precipitation and irrigation were generally very low at this site, providing about 1 kg N/ha cumulatively each year (Fig. 5). The highest N input from precipitation and irrigation water was during mid-summer each year, but it did not surpass 0.2 kg N/ha during any single month in either year.

The outflows from leaching and runoff varied substantially between the two years, from month to month within years, and among the GMSs (Table 2). In general, water outflows from subsurface leaching were greater than those from surface runoff during 2005. During that year there was more surface runoff in PostHerb than in Mulch and PreHerb plots, but runoff was equivalent in Sod vs. the other three treatments (Table 2). The time effect for surface runoff was significant, with the lowest runoff volumes observed during May and Dec. 2005—the months with the lowest precipitation that year (Fig. 5). During 2007, the surface water runoff volumes were higher than those in 2005 for the PreHerb, PostHerb and Sod treatments (Table 2). As in the previous year, Mulch plots had the lowest surface runoff volumes, and differed significantly from PostHerb plots, which had the greatest volumes of runoff during both 2007 and 2005.

The water efflux volumes through subsurface leaching during 2005 did not differ significantly among GMS treatments (Table 2). During 2007 there were treatment differences in leaching outflows—they were significantly greater in Mulch than in PreHerb plots, but similar among the other treatments. Water outflows through subsurface drainage differed substantially over time in both years, and outflow was correlated with precipitation and soil freezing/thawing events each winter. The greatest leachate outflows were observed during Oct. and Nov. 2005, and in Nov. and Dec. 2007. The lowest amounts of subsurface outflow occurred during May in both years (Table 2).

There were substantial differences for NO_3-N concentrations in runoff water among the four GMSs during 2005, but not 2007 (Table 3). For the Mulch and Sod plots, NO_3-N runoff concentrations were lower in 2005 than in 2007, and during 2005 the NO_3-N concentrations in runoff were greater in herbicide plots than in Sod and Mulch plots. However, during 2007 when N fertilizer was not applied, no differences were observed in NO_3-N runoff concentrations among the GMSs. During 2005, the lowest NO_3-N runoff concentrations were observed in Oct. and Nov., and the highest concentration was recorded in June. During 2007, the N concentrations in runoff water were significantly lower in August and higher during June, July, and October.

Leachate water NO_3-N concentrations were also much higher during 2005 than 2007 (Table 3). PreHerb plots had the smallest observed leachate NO_3-N concentrations both years, although they were not significantly different from those in other GMSs. During 2007, NO_3-N concentrations in leachate water averaged 90% lower than those observed in 2005. Mulch plots had the highest concentration of NO_3-N in subsurface leachate (Table 3). The time effect was significant for NO_3-N concentrations in subsurface leachate water during both years, but the trends were complex and appeared to be weather driven. During both 2005 and 2007, November was the month with the lowest concentrations of NO_3-N in leachate (Table 3).

The PO_4-P concentrations in surface runoff and subsurface leachate water were generally very low (ranging from 0.03 to 1.1 mg L^{-1} in leachate, and from 0.1 to 1.3 mg L^{-1} in runoff) , and did not differ consistently among GMSs during either year of this study (data not presented).

Overall, the total calculated N losses (kg $N \cdot ha^{-1}$) in runoff from this orchard during 2005 were greater in the PreHerb and PostHerb than in the Sod and Mulch treatments (Fig. 6A). During 2007, N runoff losses were again higher in the PostHerb treatment compared with other GMSs (Fig. 6C). For calculated N losses (kg $N \cdot ha^{-1}$) from subsurface leaching, Mulch plots generally had the greatest N leaching efflux during both years of observations, despite substantial variation from month to month each year (Figs. 6B and 6D).

Soil nutrient availability. Results are presented in chapter 1.

Nitrogen budgets

We compiled annual N budgets for each GMS during 2005 when N fertilizer was applied, and for 2007 when no N fertilizer was applied, normalizing calculations for an area of one hectare (Table 4). The N mineralization inputs from Mulch were two-fold greater in 2005 than in 2007, due to the recent mulch application and cumulative decomposition from previous applications in 2005. The exogenous inputs (fertilizers, irrigation and precipitation) were equivalent for all GMS treatments except Mulch, and there were substantial differences between 2005 and 2007, presumably due to the N fertilizer applications in 2005. External N inputs from the Mulch were estimated as 3 and 69 times greater than those in other GMSs during 2005 and 2007 respectively, reflecting the N inputs from mulch biomass input and decomposition.

Nutrient recycling through groundcover biomass decomposition, soil mineralization, litter fall and pruned wood constituted internal fluxes that differed among the GMSs annually, and between the two years. The combined soil N mineralization and recycling surface biomass accounted for about 60% of aggregate internal N fluxes in all treatments during both years. Total internal fluxes were lower in the two herbicide GMSs than in Mulch and Sod treatments during both years. For 2005 and 2007, harvested fruit represented more than 70% of N outputs from this orchard. Nitrogen losses through surface runoff were approximately 1-4% of N losses, and subsurface leaching represented 18-22% of N losses during 2005. In contrast, during the 2007-08 observations surface runoff N losses were two times greater than subsurface leaching N losses, except for Mulch plots. The overall balance for N among GMS treatments in 2005 was positive (inputs exceeded outputs), and it was greater in the Mulch and Sod than in other GMSs. In 2007, the overall balance for N in this orchard was negative for PreHerb and PostHerb, and positive for the Mulch and Sod treatments.

2.4 Discussion

Previous studies have shown that litter decomposition rate and N mineralization are influenced by plant residue C-to-N ratios (Chapman et al., 1988; Hansen and Coleman, 1998; Paustian et al., 1997; Wardle et al., 2001), and this was also evident in our study. Long-term soil organic matter mineralization studies indicate that amendments with low C-to-N ratios increase net mineralization (Hadas et al., 1996; Trinsoutrot et al., 2000; Whitmore and Groot, 1997). We observed that more N was released from groundcover residues in the Mulch GMS in comparison with other treatments (Fig. 2), which could be due to the lower C-to-N ratio of Mulch vegetation litter. The greater N release from litter decomposition in 2005 vs. 2007 for all GMSs (Fig. 2) could also be attributed to lower C-to-N ratios in 2005 groundcover residues because of the N fertilization that year.

Although groundcover vegetation characteristics reportedly influence litter decomposition and mineralization rates, Goh and Tutua (2004) did not find correlation between litter quality and N release in their experiment. This was also observed in our study, where groundcover litter from PreHerb plots had the lowest C-to-N ratio in 2007, but nonetheless released the least N among all treatments that year (Fig. 3). Some reports have suggested that herbicide residues may alter soil microbial communities (Yao et al., 2005; Tu, 1996), and such changes in soil microbial diversity or functionality could affect plant litter decomposition rates (Sall et al., 2006).

Abiotic factors such as soil moisture conditions may influence litter decomposition more than biotic factors, when significant differences in soil moisture content are observed under different soil management systems (Wardle et al., 2001; Wardle et al., 1993). Wetting-drying cycles in soil reportedly suppress microbial populations (Shields et al., 1974; Van Veen et al., 1987) and GMSs that buffer these effects could increase soil microbial activity over time (Wardle et al., 1993, Yao et al., 2005).

During 2005 and 2007, the Mulch treatment usually had the lowest volumes of surface runoff and the greatest amounts of subsurface leaching (Table 2). These observations reflect biomass mulches' widely reported capacities to restrain surface water flows, and to absorb and infiltrate greater amounts of precipitation compared with the bare soils typical of herbicide or cultivation GMSs (Hogue and Neilsen, 1987). A previous study of soil conditions at our site by Oliveira and Merwin (2001) showed lower bulk density, greater porosity, and higher infiltration capacities and saturated hydraulic conductivity in soil under Mulch in comparison with other GMSs; this was consistent with the increased infiltration and subsurface leaching of water observed in Mulch plots during our study.

Surface vegetation can also increase infiltration due to macropores and soil channels created by root penetration, which provide preferential flow paths when those roots die and decompose (Merwin et al., 1996). Leachate volumes were equivalent and runoff volumes were lower in the relatively weed-free PreHerb plots than in the PostHerb plots, where there was sparse groundcover vegetation late in the growing season and throughout the dormant season each year. However, in 2005 the PostHerb plots had the highest soil moisture content from late September until the end of that year (Fig. 1). Soils with high moisture content have less available pore volume for water storage capacity compared with dryer soils, and are more likely to be saturated and incapable of absorbing water during extended wetting events (Easton et al., 2007). Higher soil moisture content during the heavy rainstorms in Oct. and Nov. 2005 may have increased runoff rates in the PostHerb plots vs. the other GMSs where the soil was less saturated. During 2007, surface runoff volumes were once again higher in PostHerb compared with other GMSs. A random confounding factor in these observations was the overflow of a diversion ditch along the uphill edge of the orchard near one of the PostHerb plots, which led to brief surface flows into the adjacent plots during a few intense rainfalls in both years of this study.

The N inputs from Mulch were substantially greater than in other GMS treatments (Table 4), due to organic matter mineralization from mulch residues that increased N availability over the years and elevated the potential for N leaching from Mulch plots. However, the observed N losses through surface runoff and subsurface leaching from Mulch plots were not proportional to the high N inputs in this GMS (Fig. 6). Yao et al. (2005) attributed this prolonged retention of N in Mulch plots—even after 14 years of mulch applications—to the high C-to-N ratio in bark mulch, and the increased soil microbial activity in that GMS, which incorporated most of the N mineralized from mulch residues into microbial biomass and stable forms of soil organic matter.

In the Sod plots, uptake and recycling of soil nutrients through surface vegetation retained and utilized much of the N that might otherwise have runoff, decreasing N losses through surface runoff compared to the PreHerb treatment (Table 3 and Fig. 6). Although considerable amounts of N were mineralized from Sod residues (Figs. 2 and 3), and there was a substantial amount of white clover (*Trifolium repens* L.) in the Sod plots that presumably released N during frequent mowing in this treatment, there were minimal runoff losses of N or P from the Sod plots. Similar effects of groundcover vegetation on surface runoff and nutrient loss were reported by Haynes (1980), Skroch and Shribbs (1986), Hogue and Neilsen (1987) and Merwin et al. (1994). Contrary to the trends observed in Sod, Mulch and PostHerb treatments, during 2005 the PreHerb plots had more N loss through surface runoff than subsurface leachate (Table 3). Because of negligible groundcover residue inputs over the course of this study in the bare soil of PreHerb plots, the soil pore volume, infiltration capacities, hydraulic conductivity, and aggregate stability all decreased compared with the other GMSs (Oliveira and Merwin, 2001; Haynes, 1980). These conditions apparently exacerbated N loss from PreHerb plots through surface runoff instead of subsurface leachate, following the N fertilizer application in 2005.

Considering water quality, the average NO_3-N concentrations in surface runoff water during both years of this study ranged from 0.67 to 5.83 mg L^{-1} for all GMSs (Table 3). These values are below the US-EPA recommended water quality standards for human health, set at 10 mg L^{-1} for NO_3-N (US-EPA, 2006). However, during 2005 the NO_3-N concentrations in leachate water from Mulch and Sod plots occasionally exceeded this potable groundwater standard. The PO_4-P runoff and leachate concentration values we observed in this orchard were below the US-EPA reference condition values (20.63 to 80 mg $P{\cdot}L^{-1}$) observed in streams of upstate N.Y. (US-EPA, 2000). Compared with NO_3-N, where the concentrations in leachate samples spiked during June and July 2005 after N fertilization, there was a much smaller peak for PO_4-P concentrations in leachate and runoff samples in June 2005, following P fertilizer applications. These observations probably reflect the high P-sorption capacity of the silty clay soil in this orchard, relative to the amount of P fertilizer in that single application during 2005 (Sims et al., 1998).

Nutrient loss trends above and belowground were correlated temporally in both years of this study (Fig. 6), suggesting that N losses could be driven primarily by precipitation events rather than soil conditions associated with different GMS treatments. For example, in Nov. and Dec. 2007, the high losses of N in runoff and leaching water (Fig. 6) were coupled with rainstorm events during those months (Fig. 5). Similarly, a thaw during Mar. 2008 led to high N losses in both runoff and leaching, from all GMSs.

The N budgets for two different growing seasons and fertilizer regimes in the 13th (2005) and 15th (2007) years of this study, integrate and illustrate the underlying trends among these four GMSs. Admittedly, these N budgets do not include all possible inputs and outputs in this orchard—but they represent the first published estimates for N cycles and allocations under different orchard GMSs, based upon extensive long-term monitoring of nutrient dynamics in a representative commercial orchard. We did not have the facilities to measure particulate N deposition, gaseous N losses, or biological N fixation (which was probably substantial given the prevalence of white clover in the drive lanes and Sod plots of this orchard). However, these N budget estimates will be useful for improving the optimization of fertilizer programs in comparable orchards.

Collectively, our observations suggest that labile N in orchards is lost primarily through subsurface leaching rather than surface runoff, regardless of specific GMS effects. The N leaching losses in our study were proportionally lower than those reported by Haynes and Goh (1980a) for a fertilized apple orchard, where the observed N losses were about equally distributed between fruit crop removal and leaching, but this discrepancy may be due to lower yields in their study compared with ours. Ventura et al. (2005) reported that 8% of fertilizer N input was lost through leaching outflows in a 2-year-old pear (*Pyrus communis* L.) orchard. However, in our study the N losses through leaching accounted for 30% of mineral N fertilizer inputs; we attribute these differences to lower N demand from the mature apple trees in our study vs. the newly planted pear trees in the previous report. The internal N recycling in our orchard was lower than that reported by Haynes and Goh (1980a), who estimated that 93% of N returns came from recycling surface vegetation and 6% from leaf litter fall in the warmer climate of New Zealand where surface vegetation grows year-round—compared to 38 and 22%, respectively, that we observed in the colder N.Y. climate with a shorter growing season. Our estimates of N recycling from tree prunings pulverized *in situ* with a flail mower were similar to those reported by Greenham (1980) for a mature apple orchard in the U.K.

The generally positive balance for N supply in our study suggests that trees in Sod and Mulch plots were not N limited; but the reasons underlying that positive N balance differed between Sod and Mulch treatments. For Sod trees, the positive N balance was driven by lower yields and greater N cycling from groundcover residues and soil mineralization; in Mulch trees the N surplus was driven primarily by mulch residue humification and soil organic matter N mineralization. Considering the cumulative increase in soil organic matter and N mineralization in Mulch plots over 15 years, and the substantial surplus of N in this GMS, there could be long-term problems with N leaching in orchards that receive high annual inputs of compost, biomass mulch, or other permissible nutrient sources for certified organic production.

The N deficit for trees in the two herbicide GMSs without N fertilizer inputs in 2007 was caused mostly by decreased internal N fluxes in these two GMSs, relative to Sod and Mulch. This indicates a need for N fertilization to meet fruit crop requirements for sustained production in orchards where herbicides are used long-term for weed control (Pires and Portela, 2005). However, the N deficit in these two herbicide treatments was relatively small in our study—presumably because of relatively high soil organic matter content at this orchard—and could have been compensated with foliar applications of urea or calcium nitrate during summer cover sprays, where the potential for leaching and runoff N loss is relatively low compared to the losses from ground-applied N fertilizer applications in greater amounts.

2.5 Literature Cited

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Table 1. Total groundcover biomass production ($kg\cdot ha^{-1}$) under four GMS treatments. Values presented are means of three replicates per GMS.

GMS Treatments	**Year 2005**	**Year 2007**
PreHerb	855.7 b	526.7 b
PostHerb	1035.7 b	793.4 b
Sod	1754.0 a	2100.2 a
Mulch	966.3 b	653.3 b

Different letters within columns denote significant differences in means among GMS treatments. Letters were generated from Tukey's HSD test at $P \leq 0.05$.

Table 2. Water flow ($L\cdot m^{-2}$) from runoff and sub-surface leachate plots collected during May-Dec. 2005 and 2007. Water flow was determined as total water flowing out from each GMS treatment by averaging amounts from three replicates, and observed mean values and standard errors are presented for each corresponding GMS[†]

	Surface Runoff water volumes ($L\cdot m^{-2}$) May-Dec				**Sub-surface Leaching water volume ($L\cdot m^{-2}$) May-Dec**			
	2005		2007		2005		2007	
Treatment								
PreHerb	11.6 ± 3.8	b	32.9 ± 9.7	ab	34.2 ± 11.9	ns	44.7 ± 18.4	b
PostHerb	30.7 ± 9.9	a	87.9 ± 24.8	a	47.7 ± 13.7		41.5 ± 14.6	ab
Mulch	6.7 ± 1.1	b	6.6 ± 1.0	b	53.5 ± 16.1		61.7 ± 21.3	a
Sod	21.0 ± 6.4	ab	36.6 ± 11.4	ab	42.3 ± 11.5		51.4 ± 16.2	ab
Month								
May	1.8 ± 0.4	b	3.4 ± 2.9	e	1.3 ± 0.7	d	1.1 ± 1.0	e
June	9.1 ± 1.4	a	40.5 ± 22.8	abc	6.6 ± 2.2	c	17.2 ± 4.9	c
July	30.9 ± 16.2	a	27.6 ± 14.8	bcd	40.7 ± 11.1	bc	13.5 ± 4.5	cd
August	10.0 ± 1.2	a	76.9 ± 28.1	ab	8.6 ± 2.4	c	46.4 ± 7.8	b
September	16.6 ± 5.9	a	7.6 ± 1.9	cde	6.8 ± 2.0	cd	3.4 ± 0.9	de
October	18.5 ± 5.9	a	3.4 ± 1.6	de	116.0 ± 22.5	ab	3.3 ± 1.1	de
November	50.4 ± 14.3	a	41.5 ± 13.9	abc	129.4 ± 19.8	a	71.8 ± 10.8	b
December	3.2 ± 1.5	b	130.5 ± 36.0	a	45.9 ± 18.8	bc	241.8 ± 30.2	a

[†]- Data were transformed using Log (data + 1), and transformed means were tested for significance level. Values presented in the table are from untransformed data.

- Letters were generated from Tukey's HSD test at $P \leq 0.05$.

ns- not significantly different at $P \leq 0.05$

Table 3. Average Nitrate-N (NO_3-N) concentration (mg·L^{-1}) in runoff and leachate samples collected from June to Nov. 2005 and 2007. Values correspond to means ± standard errors from three replicates for each GMS[†].

	Runoff NO_3-N concentration (mg·L^{-1}) June-November				**Leachate NO_3-N concentration (mg·L^{-1}) June-November**			
	2005		2007		2005		2007	
Treatment								
PreHerb	5.83 ± 2.40	a	4.55 ± 3.11	ns	4.14 ± 2.82	b	0.55 ± 0.41	b
PostHerb	3.07 ± 1.02	ab	2.64 ± 0.90		13.02 ± 4.30	ab	0.77 ± 0.26	b
Mulch	1.58 ± 0.67	b	5.51 ± 1.39		10.07 ± 3.71	ab	1.60 ± 0.51	a
Sod	1.86 ± 0.85	b	3.82 ± 1.08		12.79 ± 7.81	a	0.99 ± 0.16	b
Month								
June	5.26 ± 2.25	a	4.56 ± 1.10	a	32.74 ± 17.58	a	0.93 ± 0.19	ab
July	3.35 ± 1.04	ab	4.33 ± 1.26	a	14.73 ± 6.09	ab	1.10 ± 0.52	ab
August	2.76 ± 1.13	ab	1.50 ± 0.68	b	5.37 ± 2.32	bc	0.79 ± 0.27	b
September	3.66 ± 1.45	ab	3.52 ± 1.30	ab	4.30 ± 1.14	cd	1.37 ± 0.41	a
October	1.99 ± 1.02	b	7.30 ± 3.01	a	1.57 ± 0.56	de	1.16 ± 0.38	ab
November	1.49 ± 0.54	b	3.57 ± 2.38	ab	1.31 ± 0.27	e	0.51 ± 0.25	c

[†]- Data were transformed using log transformation. Transformed means were tested for significance level. Values presented in the table are from untransformed data.

- Letters were generated from Tukey's HSD test at $P \leq 0.05$.
- ns- not significantly different at $P \leq 0.05$

Table 4. Annual nitrogen budget and balance sheet (kg N ha^{-1}yr^{-1}) for four GMS treatments in an apple orchard during 2005, when N and P fertilizers were applied, and 2007 without N or P fertilizer applications.

	Groundcover Management Systems (GMSs)							
	PreHerb (kg N·ha^{-}1·yr^{-1})		**PostHerb** (kg N·ha^{-}1·yr^{-1})		**Sod** (kg N·ha^{-}1·yr^{-1})		**Mulch** (kg N·ha^{-}1·yr^{-1})	
	2005	**2007**	**2005**	**2007**	**2005**	**2007**	**2005**	**2007**
A. EXTERNAL INPUTS								
Fertilizer application	60.0	0	60.0	0	60.0	0	60.0	0
Mulch Biomass N	0	0	0	0	0	0	169.2	84.6
Rain water	0.9	1.2	0.9	1.2	0.9	1.2	0.9	1.2
Irrigation Water	1.8	0.03	1.8	0.03	1.8	0.03	1.8	0.03
Total Inputs	**62.7**	**1.23**	**62.7**	**1.23**	**62.7**	**1.23**	**62.7 or 231.9†**	**1.23 or 85.3†**
B. INTERNAL FLUXES								
Recycling surface vegetation	15.1	19.5	20.9	21.5	23.6	29.9	25.1	24.4
Soil Mineralization	11.2	12.3	13.5	14.1	14.8	17.2	17.8	18.9
Leaf litter Fall	16.4	10.7	11.6	14.2	10.3	17.9	10.3	15.9
Pruned wood	4.1	11.5	5.6	13.2	4.8	14.5	5.2	14.9
Total internal fluxes	**46.8**	**54.0**	**51.6**	**63.0**	**53.5**	**79.5**	**58.4**	**74.1**
C. OUTPUTS								
Harvested fruit*	69.3	57.3	82.2	70.3	54.9	61.0	80.9	78.0
Surface runoff	4.0	13.5	3.1	20.8	1.4	12.8	1.2	11.1
Subsurface leaching	16.1	5.2	18.9	5.2	16.1	5.9	20.9	7.4
Total outputs	**89.4**	**76.0**	**104.2**	**96.3**	**72.4**	**79.7**	**103.0**	**96.5**
BALANCE= (A+B)-C	**20.1**	**-20.8**	**10.1**	**-32.1**	**43.8**	**1.1**	**18.1 or 187.3†**	**-21.2 or 62.9†**

†= Values including calculated N inputs from mineralization of the mulch residue.
*= Fruit yield results are presented elsewhere in chapter 1.

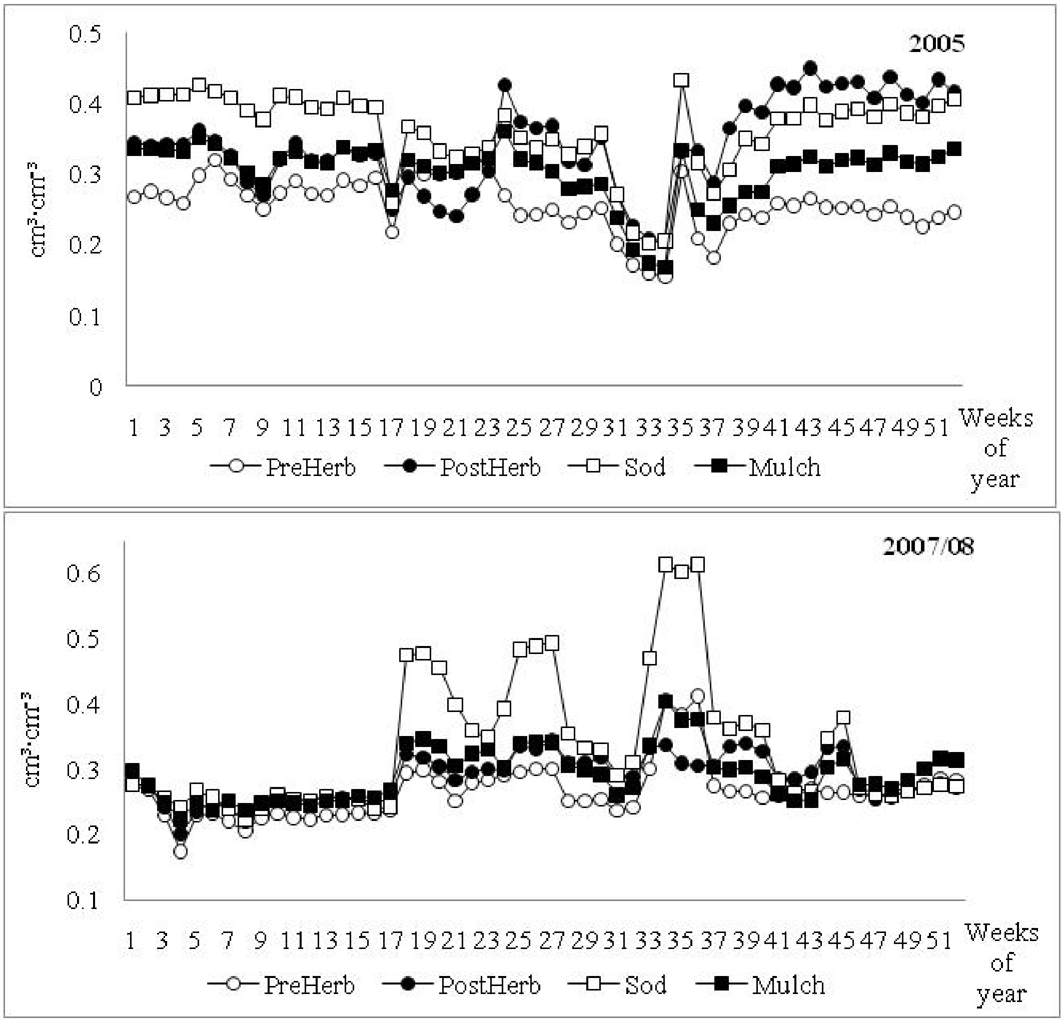


Fig. 1. Soil water moisture (cm^3·cm^{-3}) content under different GMS treatments. Daily measurements were taken for 51 weeks in 2005, and for weeks 18 to 51 in 2007, plus weeks 1 to 17 during 2008, to extrapolate for missing data.

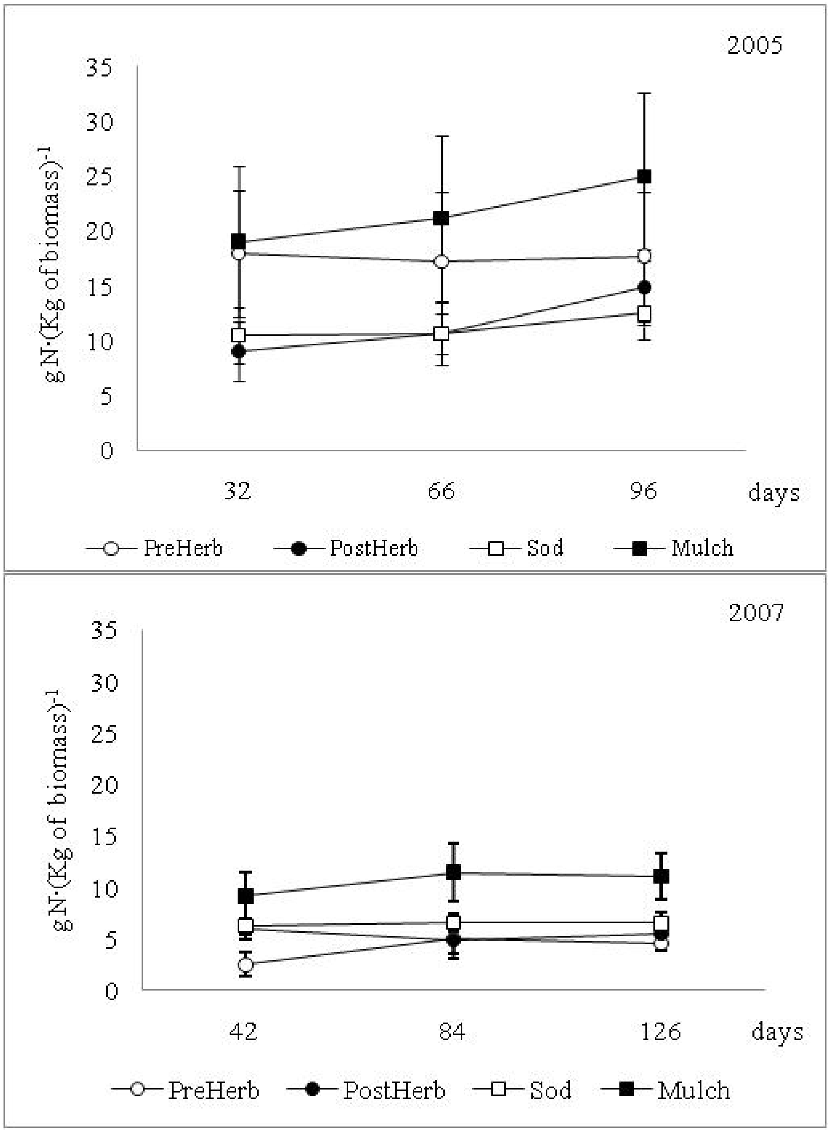


Fig. 2. Grams of N released per kilogram of biomass over time in four GMS treatments during Summer of 2005 and 2007. Values were based on 96 days in 2005 and 126 days in 2007 (n=3, mean ± SE).

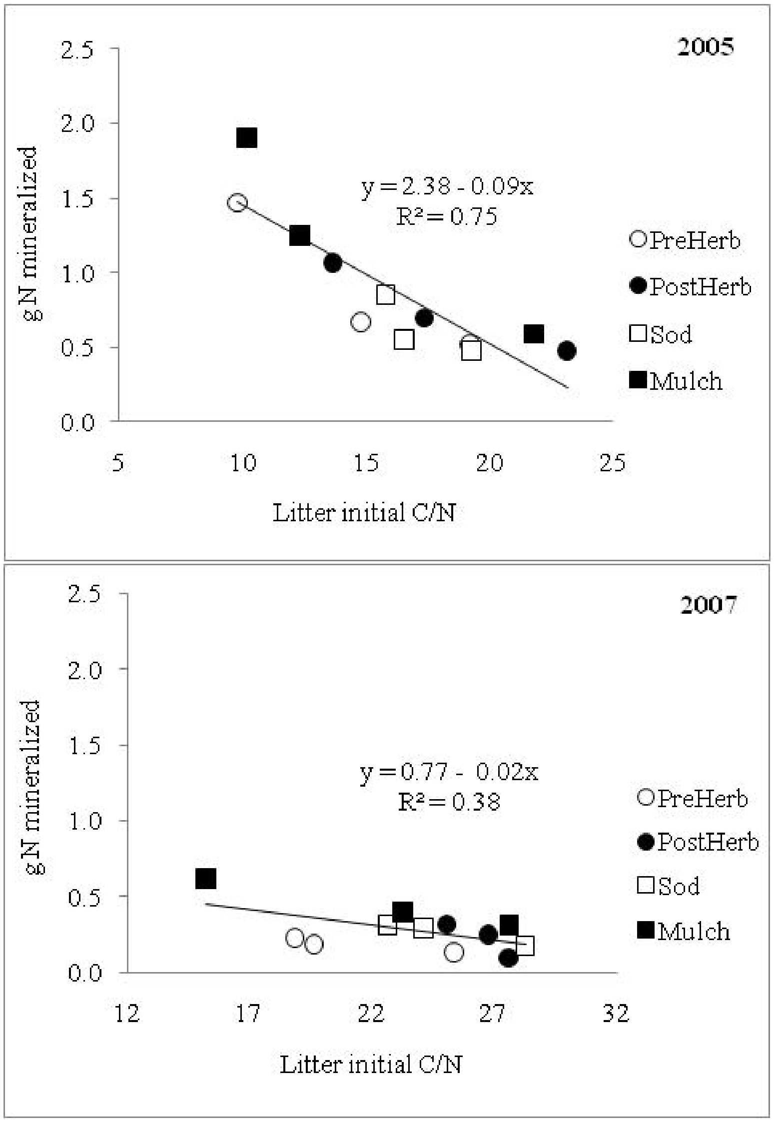


Fig. 3. Grams of N released in relation to the initial C-to-N ratio of litter residue during Summer of 2005 and 2007; P-value for model fit = 0.0002 and 0.0331, respectively.

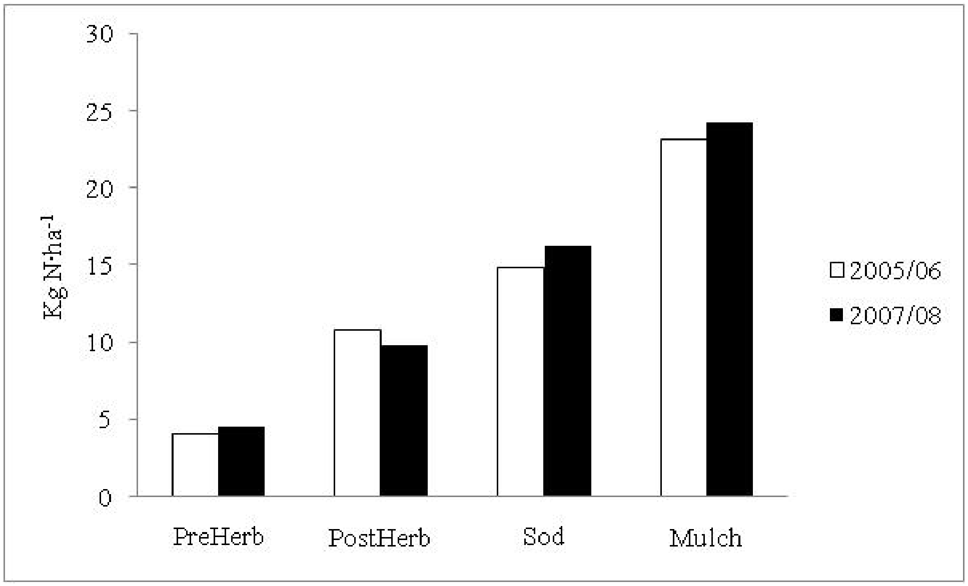


Fig. 4. Calculated estimates of soil N mineralization (kg N·ha^{-1}) under four GMSs treatments in 2005 and 2007.

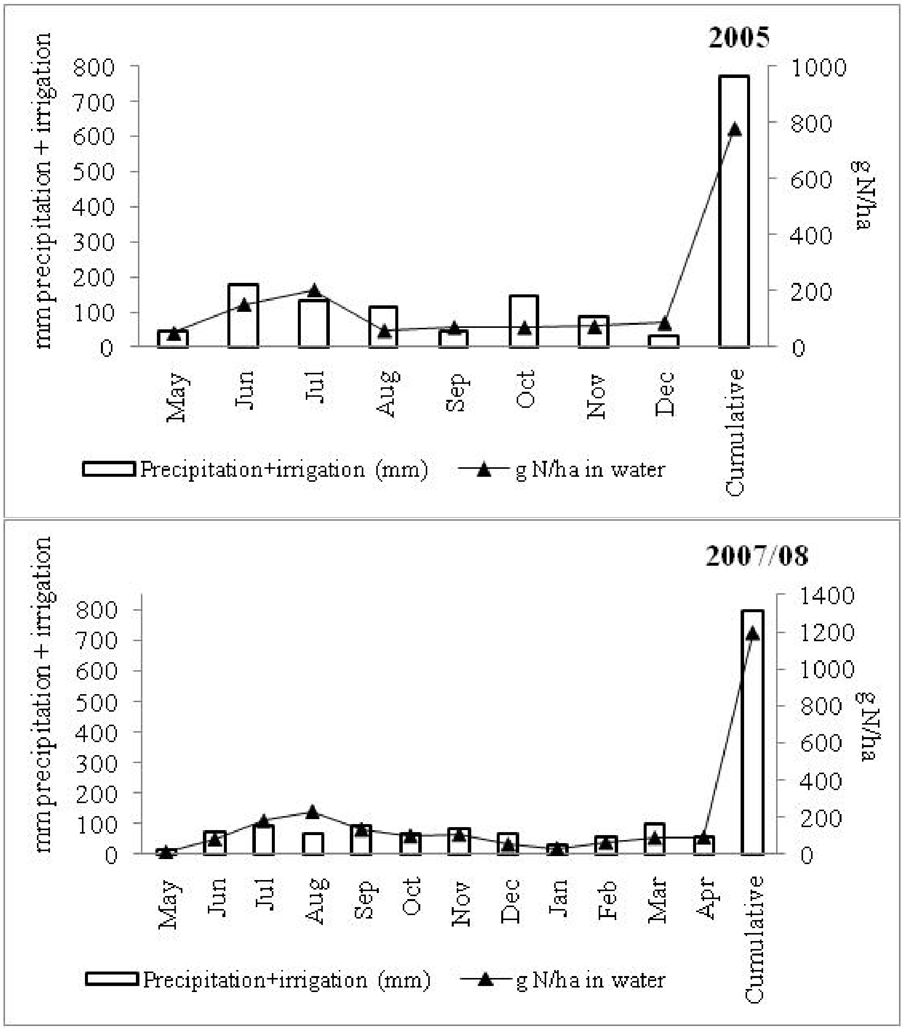
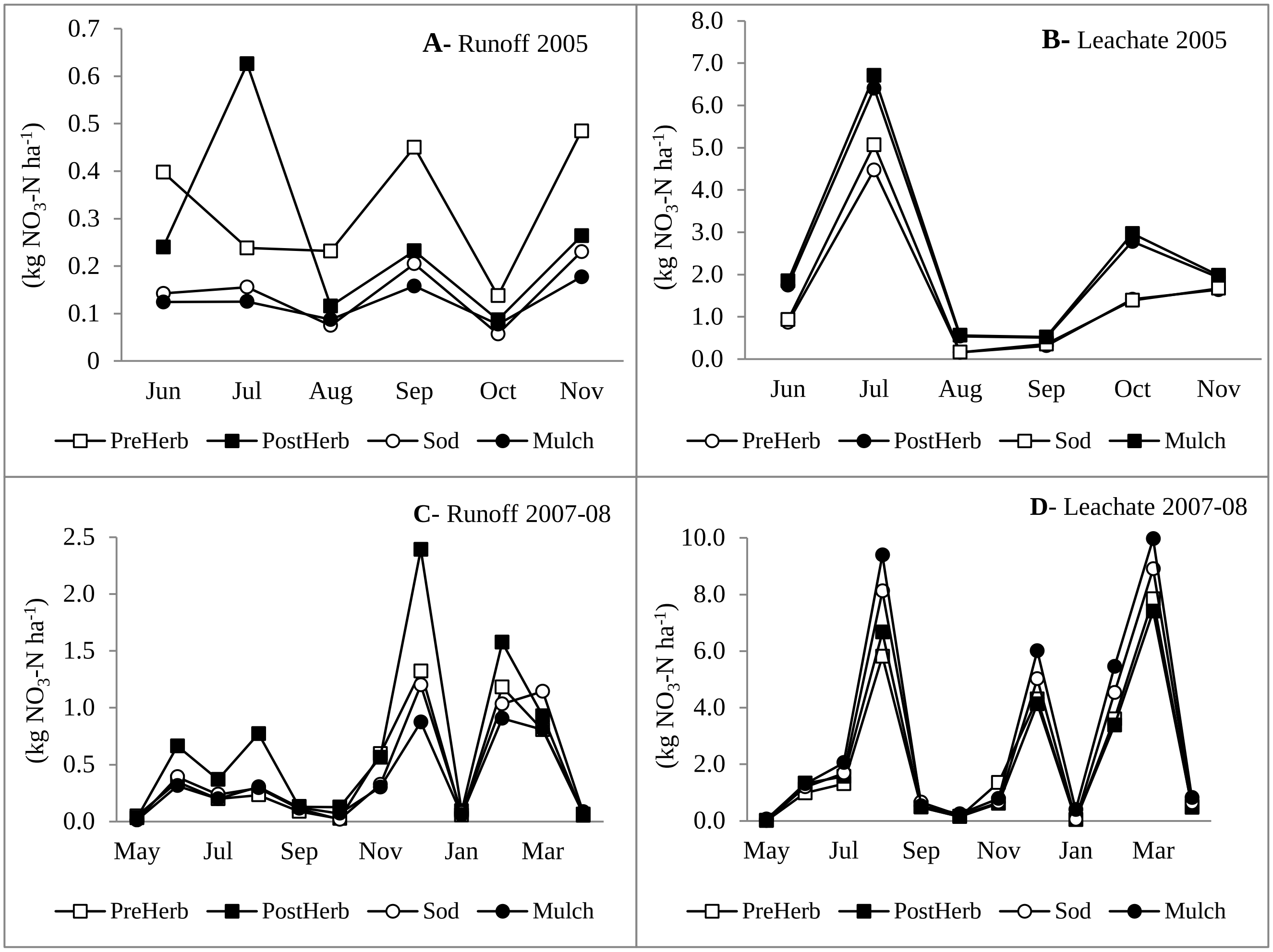


Fig. 5. Monthly precipitation plus irrigation, and calculated water-N inputs for 2005 and 2007/08, based upon irrigation water analyses at the orchard, and precipitation data from NOAA weather stations in nearby Ithaca, N.Y.



Figs. 6A-D. Estimated N losses (kg NO$_3$-N·ha^{-1}) in runoff and leachate from Jun. to Nov. 2005, May to Dec. 2007, and Jan. to Apr. 2008. Standard Errors of Means (SEMs) for PreHerb, PostHerb, Sod, and Mulch treatments in Fig. 6A were 0.2, 0.2, 0.04, and 0.02, respectively; in Fig. 6B the SEMs were 0.4; 0.5; 0.8; 0.8, respectively; in Fig. 6C the SEMs were 0.2; 0.3; 0.2; 0.04, respectively; and in Fig. 6D the SEMs were 0.3; 0.3; 0.2; 0.9, respectively. The N loss was calculated as total outflow N in each treatment (n=3) considering that GMS treatment areas (tree rows) comprised 1/3 of the orchard floor, and the other 2/3 consisted of sod drive lanes throughout the site.

CHAPTER THREE:

GROUNDCOVER MANAGEMENT SYSTEMS REDUCE RUNOFF AND SOIL EROSION, AND AFFECT TREE ESTABLISHMENT, YIELDS, AND EDAPHIC CONDITIONS IN A HILLSIDE AVOCADO ORCHARD

3.1 Introduction

Increasing land prices and urban expansion into agricultural valley regions in central Chile have constrained avocado (*Persea americana*) orchards to marginal soils and steep hills, where other crops have been impractical (Geo-Chile, 2005). Potential environmental problems associated with hillside avocado production include increased erosion and runoff when native vegetation is removed from hillsides and herbicide applications eliminate groundcover vegetation. Herbicides and fertilizers in hillside runoff water may also impact the quality of water consumed by humans and livestock in downslope areas (Pimentel *et al.*, 1995)

Site preparation for establishing hillside avocado plantations in Chile begins with removal of all native vegetation in the area to be planted, and excavating the underlying soil into raised berms where the avocado trees will be planted parallel to the slope. The bermed soil remains friable and highly vulnerable to wind or water erosion. Ditched channels between the berms channel runoff and provide few obstacles to rapid outflows down the hillsides on occasions when there are intense rainfalls (Youlton *et al.*, 2010). The climate in major avocado growing regions of Central Chile is Mediterranean type, strongly influenced by the Southern Oscillation, causing El Niño and La Niña events with alternating multiyear cycles of torrential and low rainfall events (CONAMA, 2006; Gasto *et al.*, 1987). After avocado trees are established, soil groundcover management usually consists of residual pre- and post-emergence herbicide applications to eliminate weeds and avoid competition for water and nutrients. Information on soil losses and runoff volumes generated from these hillside orchards is minimal, and there are no published studies on potential water contamination from fertilizers and herbicides in exported sediments and runoff water.

Several studies in hillside Mediterranean orchards and vineyards have reported on impacts that weed-free groundcover management systems (GMSs) have on erosion and runoff (Gomez *et al.*, 2004; Francia Martínez *et al.*, 2000; Tropeano, 1983; Uson *et al.*, 1998; Francia Martinez *et al.*, 2006), as well as the benefits of groundcover vegetation for reducing soil erosion and runoff from such orchards (Toscano *et al.*, 2004; Martinez Raya *et al.*, 2006; Kosmas *et al.*, 1996; Francia Martínez *et al.*, 2000). However, the likelihood that competition for water and nutrients between groundcovers and fruit trees could decrease yields has made growers reluctant to change their weed-free soil management systems (Gomez *et al.*, 2004.

Off-site movement of nutrients and pesticide residues in runoff is a well-documented source for pollution of surface and groundwater (Sims *et al.*, 1998 Glotfelty *et al.*, 1984; Leonard, 1990; Braun and Hawkins, 1991; Simmons and Leyva, 1994). Nonetheless, there are few reports on the effects of different GMSs on amounts of nutrient and herbicide residues exiting high input perennial crop systems established on steep hillsides. The removal of the native vegetation from these hillsides, construction of berms or terraces, and high inputs of fertilizers and herbicides in establishing such orchards are all potential sources of environmental pollution that require further study.

The present study was conducted to compare effects of different GMSs on runoff and erosion of a hillside avocado plantation, to quantify nutrient losses and herbicide residues in runoff water, and to evaluate different GMS effects on tree growth, nutrition and production, and soil physical conditions. Tree root observations using minirhizotron methods were also recorded during the study and are presented elsewhere (Chapter 4) in this dissertation.

3.2 Materials and Methods

Experimental site

The experimental site is a 0.75 ha plot with 40 to 50% slopes, located at the edge of a 300 ha hillside avocado orchard in Panquehue, Chile (Latitude 32^{0}.49’25.94’’ S, Longitude 70^{0}55’56.04’’ W). The soil type at this site is Andisols, based upon textural ratios determined by fractional sedimentation (Table 1). The site was prepared for planting in 2007, by removing all native vegetation from the hillside with an excavator. Berms approximately 50 m long and 1 m high were constructed in Dec. 2007, gathering the soil from the inter-rows into raised berms for planting the tree rows (Fig. 1). Avocado trees (‘Hass’ on ‘Mexicola’ seedling rootstocks) were planted on the berm rows in Aug. 2008, at 2 x 5 m spacing. The irrigation system consisted of one line of drippers for each berm row, with an orifice emitting 4 L hr^{-1} through two drippers about 0.2 m above and below each tree. A supplemental line of micro-sprinklers provided 34 L hr^{-1} irrigation in the ditches between berms during establishment of groundcovers in two of the GMS treatments; this line was shutdown in Dec. 2008, after the groundcovers were fully established. Three GMSs were assigned randomly to 15 plots, with 5 complete blocks containing one replicate of each GMS treatment. The experimental units were 10-m wide across the slope and 50-m long down-slope, each including two parallel berm rows planted with 20 to 25 trees, separated by a 5-m wide ditch between the berm rows.

GMS treatments

Three GMS treatments were established in Aug. 2008 and maintained as follows: 1) Bare soil (BS)— a combination of two herbicides (glyphosate and terbuthylazine) was applied over the entire plot surface (berms and ditches), at 1.44 and 3.0 kg active ingredient (a.i) ha^{-1}, respectively. Terbuthylazine was applied in Aug. 2008, June 2009 and May 2010. Glyphosate was applied in Aug. 2008 and 2009, and in June 2010; 2) Vegetation strip (VS)—post-emergence glyphosate applied in a 1-m wide strip centered on each tree berm row at a rate of 1.44 kg a.i. ha^{-1}, but not to the inter-row ditches, in Aug. 2008 and 2009, and during May 2010, to suppress weeds during the growing season. In Aug. 2008 a mixture of ryegrass (*Lolium rigidum* var. *wimmera*) and the naturalized legume Hualputra (*Medicago polymorpha sp.*) was seeded in the ditches between the VS berm rows at a rate of 75 and 30 kg ha^{-1}, respectively. During Aug. 2009 the groundcover in ditches was suppressed with a contact herbicide (paraquat) applied at a rate of 0.9 L a.i. ha-^{1}. In Feb. 2010 the groundcover was mowed to 0.1-m height using a weed trimmer, to prevent possible brush fires during the summer; 3) A complete groundcover (GC)—The same mixture of ryegrass (*Lolium rigidum var. wimmera*) and Hualputra (*Medicago polymorpha sp.*) as in the VS treatment was established over the entire surface of the plots (berm rows and ditches) in Aug. 2008, and mowed to 0.1-m height during Feb. 2009 and 2010, with its biomass residues left on site.

Orchard management

The avocado trees were managed typically for hillside commercial orchards in central Chile (Gardiazabal, 1998). Trees were fertigated in 2008, 2009, 2010 and 2011, applying urea (46N-0P-0K), Entec 21 (21N-0P-0K), potassium nitrate (13N-0P-44K), zinc sulfate ($ZnSO_4$) and phosphoric acid (0N-31P-0K) (Table 2).

Runoff and erosion catchment system

Fifteen runoff/erosion catchment plots (25-m long by 5-m wide), consisting of two adjacent berm rows and the ditch between each berm-row pair, were established during Fall 2008, just before trees were planted. At the lower end of each catchment a plywood weir was embedded across the ditch to channelize sediments and runoff through a polyvinyl chloride (PVC) pipe into a 120-L high-density polyethylene (HDPE) barrel secured by four metal posts driven 1 m into the ground. Outflows from the barrels were measured with tipping buckets attached to a HOBO Data Logger model UA-003-64 (Onset Technologies, Bourne, Mass.) to record the number of calibrated tips and measure overflows. This system enabled us to measure continuous outflows of water from each plot during each rain event, over three years. To estimate soil losses, a water sample was taken from each barrel following precipitation events, after stirring the water in barrels to bring sediments into suspension. Samples were filtered through Whatman

Glass Microfibre Filter paper (Fisher Scientific, N.H.), sediments were oven-dried at 40 ^{0}C for several days to constant weight, and sediment dry weights were recorded for each sample and rain event.

Data-logging soil moisture and temperature.

Soil-temperature and moisture-monitoring probes were installed in each plot for continuous datalogging of soil conditions. Volumetric soil water content and temperature at 0.05-m depth in soil were recorded using EC-TM (moisture-temperature) sensors (Decagon Devices, Wash.) logged with Em50 five-port data-loggers (Decagon Devices, Wash.). This enabled us to record data at bi-hourly intervals continuously year-round from all 15 GMS plots. Volumetric soil water content and temperature data were averaged biweekly for each plot to facilitate trends interpretation and presentation. When soil-monitoring data were missing due to transient technical problems, missing values were estimated by extrapolating from averages of comparable time intervals for other plots of the same GMS treatment.

Tree growth and fruit yield

Tree-trunk cross-sectional area (TCSA) was recorded annually during the winter season (July-August) at a permanently marked height (0.3 m above ground) to estimate annual and cumulative increases in tree size. Fruit yield was recorded in 2011, as harvested fruit weight (kg) per tree, number of fruit per tree and average fruit size. During 2008, TCSA was recorded for all trees in each plot. However, during 2009 several trees had to be replaced in the GC plots due to hare (*Lepus europaeus*) damage to the lower tree trunks. TCSA and yield data were collected from the centermost 15 healthy trees in each plot (to minimize edge effects) and averaged to represent a treatment mean for respective GMS treatments. During 2011, subsamples of 10 fruits per tree were individually weighed to estimate fruit size distribution. Yield efficiency of the trees in each GMS treatment was calculated by dividing fruit yield (kg tree^{-1}) by TCSA (cm^2).

Leaf nutrient content

Recently matured leaves were sampled in July from the centermost 15 trees in each plot (Lahav and Whiley, 2002). Leaves were rinsed with distilled water and oven-dried at 40 ^{0}C for several days to constant weight. Samples were sent to Cornell Nutrient Analysis Laboratory (CNAL) and analyzed for macro- and micro-nutrient concentrations by inductively coupled Argon plasma spectroscopy (ICP AES model Spectro CIROS vision, Kleve, Germany); leaf C and N content was determined by Dumas combustion methods.

Water analysis for nutrient concentrations and herbicide residues.

After each precipitation event, the water in each barrel was stirred to homogenize its content, and a 250 ml sample was collected. Samples were filtered through Whatman Glass Microfibre Filter paper (Fisher Scientific, N.H.) and frozen at -5 ℃ for subsequent analyses. Water N and P concentrations were determined, using automated cadmium reduction and ascorbic acid methods, respectively (Clesceri *et al.*, 1998), followed by continuous-flow colorimetry (Perstorp Analytical, Alpkem, Ore.). Each runoff sample was also analyzed for herbicide residues. Terbuthylazine analyses were carried out using enzyme-linked immunosorbent assay (ELISA) kits with minimum detection limits of 0.31 μg L^{-1} (Strategic Diagnostics Inc., Newark, DE). Concentrations were determined spectrophotometrically (at 450 μm) in a dedicated RPA-1 spectrophotometer.

Soil nutrient availability

Soil samples were collected during mid-winter from 2009 to 2011 with a 0.02-m-diam metal core from 0 to 0.1-m depth, beneath the tree canopy along the berm-rows. Samples were sent to the CNAL and analyzed for plant available nutrients as follows. Macro- and micronutrients were extracted in Morgan’s solution (0.72 *N* NaOAc + 0.52 *N* CH_3COOH, buffered at pH 4.8), using a soil-to-solution ratio of 1:5 (v/v). The extracted mixture was filtered and passed through an automated rapid flow analyzer to detect plant-available PO_4-P, while the rest of the macro- and micro-nutrients were quantified by inductively coupled argon plasma (ICP) spectrophotometry. Soil pH was determined using 1:1 (v/v) soil to 0.01 M $CaCl_2$ solution, and total C and N by Dumas combustion. Soil organic matter was determined by loss on ignition at 550 ^{0}C.

Physical Soil Properties

Intact soil samples were collected using two stainless steel cores, taped vertically together, for a 0.07-m internal diameter and a 0.12-m depth. Cores were driven into the soil and lifted out with a hand-shovel, to minimize changes to field conditions within the soil cores. Intact samples were prepared for analysis by carefully separating the taped cores into upper and lower profiles, which represented 0-0.06 m and 0.06-0.12 m soil depth, respectively. Each core was evaluated for soil bulk density, porosity, and available water capacity, using procedures described by Moebius et al. (2007), Moebius-Clune et al. (2008) and Karunatilake and VanEs (2002). Nylon gauze was attached to the bottom of each steel ring with a rubber band to prevent soil loss. Sample cores were saturated (Ψ= 0 kPa) in their rings by raising the water table slowly during 48 h to prevent trapping air in soil pores. Macroporosity (pores >1000 μm diam) was determined gravimetrically by allowing the saturated cores to drain for 3 h, to reach an assumed equilibrium water potential at Ψ= -0.3 kPa. A pressure-cell apparatus (Karunatilake and Es, 2002) was then used to determine soil water retention at -1.0, -3.0, -10.0 and -30.0 kPa matric potentials. Soil cores were then oven-dried at 105 ^{0}C and weighed to determine bulk density. Microporosity (pores 0.2-30 μm diam) at Ψ = -1500 kPa was measured on a ceramic high-pressure plate. Available water capacity (m^3 m^{-3}) was calculated as the difference in water loss between Ψ = -10.0 and Ψ = -1500 kPa. Wet aggregate stability of small aggregates (0.25-2 mm diam) was measured from disturbed samples using a rainfall simulator (Ogden *et al.*, 1997). Samples were oven-dried (40 ℃) and shaken over stacked 2 mm and 0.25 mm mesh sieves and a catch plate. A single layer of 0.25 to 2 mm aggregates was spread on a 0.25 mm mesh sieve and placed 0.5 m below a rain simulator, calibrated to delivered 1.25 cm of water in 5 min. Soil and other particles retained on the sieve and disaggregated soil that fell through the sieve onto a filter were collected, dried, and weighed to determine wet aggregate stability.

Precipitation record

During 2008, rainfall amounts were recorded by a standard cylindrical rain gauge located at the bottom of the hillside. During 2009 and 2010, precipitation amounts and rates were recorded by a RAINEW-111 rain gauge (Premiere Products, Columbus, NE), logged with HOBO data-loggers. There were two rain gauges at the site, one in the upper and another in the lower rows of plots; data presented are the average of both rain gauges.

Data analysis

A repeated measurement model (JMP, Version 7. SAS Institute Inc., Cary, N.C., U.S.) was used to analyze data within years. When there were significant interactions between treatments and years, data were analyzed as a one-way analysis of variance model for each year. When significant effects were indicated, means were compared using Tukey's HSD at $P < 0.05$, unless otherwise noted in text and tables. For the year 2010, data were analyzed using a logistic regression model to determine if treatments had an effect on the presence or absence of surface runoff, and a one-sample T-test was used to test whether the runoff observed in the BS treatment was significantly different from zero.

3.3 Results

Tree growth and fruit yield

During the first three years after planting, trees in BS plots were larger than those in GC plots (Fig. 2) and also larger than VS trees in 2010 and 2011. No significant differences were observed between VS and GC tree size during 2010 or 2011.

The first avocados were harvested in 2011, three years after tree establishment, and the BS trees were more productive than the VS and GC trees (Table 3), with significantly higher numbers of fruit and more kg of fruit per tree. No significant differences were observed for fruit size among the three treatments.

Leaf nutrient content

Although there were differences in leaf nutrient content among the treatments in 2009, 2010 and 2011 (Table 4), there were no sustained trends related to GMS treatments during the three years of evaluation. No significant differences were observed in total N or C content in avocado leaf tissue among the treatments for any of the three years. No nutrient deficiency symptoms were observed in trees of any GMS treatments.

Runoff, erosion and nutrient losses

During the first year of this study (2008), three precipitation events were recorded between July and August (Table 5). Since the GMS treatments were not fully established at the time of these rain events, the data collected from all 15 plots were pooled and presented as a baseline record for runoff and erosion rates at the outset of this study. The largest runoff event was recorded during the last rainfall of 2008, with an average volume across all treatments of 3.01 mm. The biggest soil loss was recorded during the first rainfall event of that year, with an average loss across treatments of 1.9 MT ha^{-1}. The NH_4-N and PO_4-P concentrations in runoff water were similar for all precipitation events, averaging 0.1 and 0.2 mg L^{-1}, respectively (Table 5). Runoff water NO_3-N, total N (TN) and dissolved organic C (DOC) concentrations were highest in the first precipitation event, with average concentrations of 0.5, 0.1 and 3.6 mg L^{-1}, respectively. The greatest nutrient losses in runoff water were observed during the last rainfall event of 2008, with total losses of 14.0, 9.9 and 44.1 g ha^{-1} of inorganic-N, PO_4-P and TN, respectively.

During 2009, runoff volumes, soil losses, PO_4-P, TN and DOC losses were consistently higher in the BS plots than in the VS and CG treatments, with no significant differences between the latter two treatments (Table 5). The NH_4 and PO_4 concentrations in runoff water were greater in VS and GC than in BS plots, and no statistical differences were observed among treatments for NO_3 and DOC concentrations in runoff water. The TN concentrations were highest in GC runoff water, followed by the VS and BS treatments. During the largest single rainfall event on 28 June (58.9 mm), the BS plots generated 73 times more runoff and 2000 times more soil erosion loss than the GC plots. During five rainfall events observed in 2009, the GC plots only produced detectable runoff in the first three rains.

In the winter of 2010, three precipitation events occurred. The two treatments with groundcover vegetation (GC and VS) did not generate detectable runoff in any of these three rainfall events. Even though there were fewer rainfall events than in 2009, the BS plots generated higher volumes of runoff and soil losses in 2010 than in the previous years (Table 5). Runoff volumes in the BS plots increased throughout the rainy season in 2010, and the largest runoff occurred in the last rainfall event of that year, with an average across all BS plots of 2.03 mm. The most soil loss was observed in the second rainfall of 2010 after 108.7 mm of precipitation, with an average soil loss from BS plots of 1769.7 kg ha^{-1}. Nutrient concentrations and losses in runoff also increased throughout the rainy season that year. The greatest nutrient losses in runoff occurred during the last rainfall event of 2010, with total losses of 16.2, 12.3 and 28.5 g ha^{-1} of inorganic-N, PO_4-P, and TN, respectively—the highest nutrient losses observed during this entire study (Table 5).

Herbicide residues

The average concentrations of terbuthylazine in runoff water from the BS plots were 55.4, 79.9, and 64.2 μg L^{-1} in 2008, 2009 and 2010, respectively. The herbicide concentrations were highest in the runoff event following annual herbicide application, with concentrations as high as 487.2; 260.4 and 388.3 μg L^{-1} in 2008, 2009 and 2010, respectively. Even though terbuthylazine was applied only in the BS plots, traces of the herbicide were detected in runoff water samples from the other treatments too, though in much lower concentrations than those in the BS plots. During 2008 and 2009, the average concentrations of terbuthylazine in runoff water from the VS and GC plots were 15.4 and 5.3μg L^{-1}, respectively.

Soil Physical Properties and nutrient availability

There were substantial differences in soil physical properties among GMS treatments from 2009 to 2011. Soil bulk density was greater in the BS plots than in the GC plots (Table 6). Soil macro-porosity and aggregate stability were significantly greater in the GC plots than in the other two treatments, but no statistical differences were observed among treatments for soil meso- and micro-porosity.

There were sustained trends in the relative availability of essential plant nutrients in soil under the GMSs during three years of observations (Table 7). Soil K and Mg availability, and soil pH were significantly higher in GC than in the BS treatment, while Zn concentrations were higher in the BS plots than in the GC treatment. The GC plots had greater soil pH, and P, K, and Cu concentrations than the VS plots. Soil organic matter (SOM) and total C content differed substantially among treatments; the highest SOM content was observed in the GC plots, followed by the VS and BS treatments. Total N was greater in soil of GC plots than in the other two treatments, and C-to-N ratios were lower in BS than in the VS and GC treatments. There were no significant differences observed among treatments for soil Ca, Fe, Al, Mn and NO_3-N availability during this study.

Trends in soil temperature and water content from 2009 to 2011 were complex and varied among years as well as among GMS treatments (Fig. 3). Soil water content was significantly different among all three treatments ($P< 0.0001$), with average soil water contents ranking GC >VS >BS during the timespan of this study. No significant differences were observed among treatments for soil temperatures (data not shown).

3.4 Discussion

Short-term studies comparing different GMSs have shown that competition for nutrients and water between weeds or mowed sod covers and fruit trees can cause substantial growth reductions and yield losses, in comparison with weed-free GMS treatments. As previously reported by others (Robinson and O'Kennedy, 1978; Shribbs and Skorch, 1986; Welker and Glenn, 1989), we also observed reduced tree growth and fruit yield in the GC compared with BS plots (Fig. 2 and Table 3). However, in our irrigated study soil water content in GC plots was actually greater than that in the BS plots (Fig. 3), suggesting that trees in the GC and VS treatments were not experiencing more water stress than BS trees. Moreover, there were no significant GMS differences over time for leaf nutrient content, which suggests that trees in the VS or GC plots were not more stressed than BS trees by nutrient deficiencies. Total soil N and C contents were also greater in the GC than in the BS treatment, probably due to N mineralization from groundcover residues and N_2 fixation by the Hualputra legume groundcover (Ovalle *et al.*, 2006; Nyborg *et al.*, 1995b; Janzen *et al.*, 1998; Solberg *et al.*, 1998; Kumar and Goh, 1999).

During decomposition of cover crop residues there may be an initial period of soil N-immobilization, followed by a period of net N re-mineralization (Kumar and Goh, 1999; Recous *et al.*, 1999). The length of this lag period depends on the C-to-N ratios of the crop residue (Reinertsen *et al.*, 1984), lignin and polyphenol contents (Kumar and Goh, 1999), and initial soil N concentrations (Reinertsen *et al.*, 1984; Recous *et al.*, 1995), among other factors. In the present study, uptake of N by groundcovers, retention of N during initial groundcover residue decomposition, and the low initial SOM content at this site, could have interacted to reduce soil N availability transiently in the GC and VS plots compared with the BS treatment (Nyborg *et al.*, 1995a). This temporary restriction in soil N availability may explain the decreased tree growth and fruit yield of trees in the VS and GC treatments compared to BS.

Although groundcovers are relatively more efficient than fruit trees in capturing the N mineralized by decomposing groundcover residues (Haynes and Goh, 1980; Sanchez *et al.*, 2003; Yao *et al.*, 2005), during the first years of our study there were minimal groundcover residues to be recycled, and the groundcover vegetation was directly competing for nutrients and water with the newly planted avocado trees. This initial competition, in a vulnerable stage for the newly planted avocado trees, might have been masked in the overall effects of treatments on soil moisture and leaf nutrient content, but it could have been enough to affect tree growth. Other factors such as tree-groundcover root competition could have also resulted in the observed growth reductions and yields losses in the GC and VS, compared with BS treatment trees (McMurtrie and Wolf, 1983).

Welker and Glenn (1989) observed that growth of young peach (*Prunus persica*) trees was proportional to their surrounding weed-free area, and suggested that restricted tree soil volume due to sod competition resulted in smaller peach root systems and consequently smaller trees. However, in our study the growth of trees in both the GS and the VS plots was equivalently reduced, despite the closer groundcover proximity to avocado trees in the GC vs. the VS treatments. In this context it is also noteworthy that the winters where evergreen fruit trees are cultivated are generally warmer than those where deciduous fruit trees are grown. These warmer temperatures during humid winter months, and the frequent irrigation during drier summer months (November through March) at our site in Chile, allowed for continuous growth of weeds and groundcovers throughout the year. These conditions presumably increased competition between groundcover vegetation and newly established avocado trees, and the yearly post-emergence herbicide application in the berm rows of VS plots may have not been sufficient to eliminate weed competition. Similar effects on tree growth and fruit yield were observed by Castro and Pastor (1994) and Wright et al. (2003) in GMS studies in an olive grove and citrus orchard, respectively.

Numerous GMS studies have shown the effectiveness of groundcovers for runoff and soil erosion control in perennial fruit plantings on hillsides (Francia Martinez *et al.*, 2006; Gomez *et al.*, 2003; Martinez Raya *et al.*, 2006; Youlton *et al.*, 2010). Interception of rainfall by groundcovers dissipates the direct impact of raindrops on the soil surface, ultimately reducing runoff and erosion (Francia Martinez *et al.*, 2006). We observed a significant reduction in runoff and erosion in both groundcover treatments compared to the bare soil treatment, and similar observations were reported by Youlton et al. (2010) and Francia-Martinez et al. (2006), in avocado and olive orchards under different GMS treatments.

During 2008, before the establishment of GMS treatments in our study, runoff volumes increased and erosion rates decreased throughout that first wet season. The high erosion rates observed at the beginning of the rainy season in 2008 suggest high vulnerability of the newly constructed berms to rainfall, as a consequence of the disturbance of the soil during excavation in the swales and mounding up the berms. On the other hand, the increased runoff toward the end of the wet season in 2008 probably resulted from soil compaction due to preceding rain events that year, leading to soil-surface sealing that reduced infiltration and increased runoff (Lindstrom and Onstad, 1984; Gomez *et al.*, 1999; Gomez *et al.*, 2004). Saturated soil conditions at the end of winter in 2008 might also have reduced infiltration and increased runoff compared to the initial rainfall events that year (Bissonnais *et al.*, 1995). These results highlight the importance of protecting soil from erosive forces after the construction of berms and during hillside orchard establishment, at a time when soil is especially vulnerable to erosion due to its recent disturbance and the lack of surface vegetation or crop residues to protect the soil surface.

Soil compaction in the BS plots was greater than in the GC treatment, as reflected by the higher soil bulk density and lower macro-porosity in the BS compared to the GC plots (Table 6). Management effects on soil aggregate stability influence susceptibility to soil degradation, and are fundamental for promoting soil conservation (Boix-Fayos *et al.*, 2001; Ramos *et al.*, 2010). In our study, aggregate stability increased in berm soil beneath GC compared with BS and VS treatments. Organic substances supplied by roots are a source of energy for microorganisms in the rhizosphere, and materials produced by these microorganisms (e.g. mucilaginous polysaccharides) play an important role in the stabilization of soil aggregates (Gale *et al.*, 2000; Six *et al.*, 2004; Ramos *et al.*, 2010). In addition, soil organic matter content, which is correlated with aggregate stability (Oades, 1984; Caravaca *et al.*, 2002, Ramos *et al.*, 2010), probably contributed to the greater aggregate stability observed in the GC plots, which in turn reduced runoff volumes and soil erosion in that treatment.

The increased SOM content in GC and VS plots—attributed to groundcover residues and rhizosphere decomposition (Manns *et al.*, 2007)—also improved soil fertility and soil physical conditions, and facilitated soil-water storage during the summer months. The assimilation of N and P from fertilizers and the legume groundcover into microbial biomass and SOM apparently reduced nutrient losses through surface runoff in the GC and VS, in comparison to the BS plots. Total nutrient losses in our study were lower than those reported in the literature for other perennial fruit crops (Ramos and Martinez-Casasnovas, 2006; Francia Martinez *et al.*, 2006; Duran Zuazo *et al.*, 2004; Ramos and Martinez-Casasnovas, 2004). However, NH_4-N concentrations in runoff during the first rainfall events of 2009 exceeded both the 0.5 mg L^{-1} threshold concentration for public water supplies (Hütter, 1994), and the 5 mg L^{-1} limit recommended for irrigation sources (Ayers and Westcot, 1985) .

Average PO_4-P concentrations in most runoff events in all GMS treatments exceeded established limits of 0.05 mg L^{-1} (US-EPA, 1976) that may lead to eutrophication of surface waters. The P concentrations in runoff remained below the critical threshold level of 2 mg L^{-1} for agricultural water use (Ayers and Westcot, 1985). However, since total nutrient losses were estimated based on dissolved nutrients in runoff water, our results probably underestimated the total amounts of nutrients lost, because we did not account for nutrients bound to soil in particulate forms. Particulate P can account for 75-95% of the P losses in runoff water from agricultural land, according to reports that P losses in sediment transport were 2.8 fold higher than those dissolved in runoff water (Sharpley *et al.*, 1994; Duran Zuazo *et al.*, 2004).

Considering water quality, the average terbuthylazine concentrations in BS treatment runoff water during this study (55.4 to 79.9 µg L^{-1}) were substantially higher than the guideline values for pesticide residues in drinking water, set at 7 µg L^{-1} for terbuthylazine (Younes and Galal-Gorchev, 2000), and the European Union maximum level of 0.1 µg L^{-1} in water intended for human consumption (Hamilton *et al.*, 2003). Terbuthylazine can also be transported through sediments, due to its moderate sorption and a relatively long persistence in soils (Blanchoud *et al.*, 2007), increasing the risk of water contamination and bioaccumulation in aquatic organisms (FCS, 2007). The concentrations of this herbicide in runoff from our site are therefore a real concern for this region of Chile.

3.5 Conclusion

Our study demonstrated substantial impacts of GMSs on soil erosion and runoff in hillside avocado orchards, and suggests the potential for protecting these hillsides by managing groundcovers to reduce erosion and associated environmental problems. The observations are consistent with other studies demonstrating the capacity of vegetative covers to reduce erosion and surface runoff on agricultural land. Likewise, nutrient losses were reduced by groundcovers in comparison with the bare soil herbicide treatment, which could reduce nonpoint-source pollution of drinking water sources. The groundcovers also improved soil physical conditions compared with the conventional weed-free herbicide GMS used in Chilean avocado orchards—increasing soil organic matter content and improving soil edaphic conditions.

However, the use of groundcovers as an alternative GMS for hillside avocado orchards also had negative effects on tree growth and productivity during the first three years after orchard establishment. These economic downsides partly explain the reluctance of avocado growers to change their soil management practices. However, long-term studies of alternative GMSs in other orchard crops have shown that continued interactions of fruit trees with competing groundcover vegetation sometimes enable trees to adapt and compensate or avoid groundcover competition for water and nutrients (Atucha *et al.*, 2011a; 2011b). Furthermore, the long-term deterioration of soil physical conditions and biological activity in weed-free orchard soils (Oliveira and Merwin, 2001; Yao *et al.*, 2005) may eventually be more detrimental for orchard productivity than the short-term groundcover competition during initial orchard establishment.

The use of groundcovers to mitigate soil erosion and runoff during hillside orchard establishment is a viable management practice that could be especially beneficial during the first years of avocado orchard establishment, when soil in this hillside berm production system is most vulnerable to erosion. Groundcover establishment between tree rows, combined with non-residual herbicide applications within the bermed tree rows during the growing season, may provide an optimal combination soil conservation and tree performance during this period.

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Table 1. Characteristics of the soil in each replicate block prior to the establishment of GMS treatments. Soil particle size distribution was based on the USDA system. OM = soil organic matter content; total N and total C based on Dumas combustion analysis.

Block	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	OM (g kg^{-1})	Total N (mg g^{-1})	Total C (mg g^{-1})	Slope (%)
B1	142.9	349.9	507.2	3.1	0.5	6.9	52
B2	132.6	334.1	533.3	2.4	0.5	5.0	49
B3	134.9	269.5	595.6	2.6	0.6	5.7	32
B4	189.6	270.1	540.3	3.2	0.8	9.6	54
B5	201.5	330.4	468.0	3.1	0.7	8.9	48

Table 2. Orchard fertigation equivalent nutrient applications from 2008 to 2011.

Year	**Month**	**N** (Kg ha^{-1})	**P** (Kg ha^{-1})	**K** (Kg ha^{-1})	**Zn** (Kg ha^{-1})
2008	Aug.	42.8	17.6	7.3	
	Sept.	42.8	17.6	7.3	
	Oct.	42.8	17.6	11.6	
	Nov.	61.6	17.6	11.6	
	Dec.	61.6	17.6	11.6	
2009	Jan.	42.8	17.6	11.6	
	Feb.	42.8	17.6	11.6	
	Mar.	42.8	17.6	11.6	
	Apr.				
	May			7.3	
	June			3.5	
	Jul.			3.5	
	Aug.				8
	Sep.				12
	Oct.				16
	Nov.				16
	Dec.				16
2010	Jan.	26			16
	Feb.				12
	Mar.				8
	Apr.	46.8			
	Aug.				8
	Sep.				16
	Oct.	52.5			24
	Nov.				24
	Dec.				24
2011	Jan.	52.5			12
	Feb.				8

Table 3. Number of fruits, kg of harvested fruit, and average fruit size (g) per tree in each groundcover management system treatment at first harvest, in 2011. Letters of mean separation within each column represent Tukey's honestly significant difference (HSD) test at *P*≤0.05.

GMS	# Fruit	Kg tree^{-1}	Fruit size (g)
BS	27 ± 4 a	5.0 ± 0.9 a	185.9 ± 4.3 ns
VS	11 ± 2 b	2.0 ± 0.4 b	195.5 ± 16.9
GC	7 ± 1 b	1.4 ± 0.2 b	213.9 ± 19.3

ns= No significant differences

Table 4. Effects of GMSs treatments on foliar nutrient concentrations (mg/kg). Values are means of five replicates. Within each year and for each variable, treatment means within rows followed by different letters differ at P ≤ 0.05 by Tukey' HSD test.

	2009						2010						2011					
Variable	**BS**		**VS**		**GC**		**BS**		**VS**		**GC**		**BS**		**VS**		**BS**	
B	6.9 ± 0.2	a	6.1 ± 0.4	b	9.7 ± 1.2	a	12.8 ± 0.8	b	24.0 ± 2.5	a	27.0 ± 0.8	a	21.6 ± 5.4		21.0 ± 4.7		19.22 ± 2.7	
Na	11.6 ± 1.0 b	b	10.9 ± 0.9		11.5 ± 1.8		19.2 ± 4.4	b	12.8 ± 3.1	b	48. 2 ± 23.9	a	157.1 ± 1.5		161.9 ± 3.5		163.5 ± 5.9	
Mg	4381.4 ± 113.8		4205.3 ± 195.0		4480.7 ± 277.2		4877.6 ± 149.3	a	4287.0 ± 367.7	ab	4118.0 ± 197.0	b	6413.6 ± 237.3	a	5563.7 ± 301.7	b	5622.7 ± 216.5	b
Al	45.4 ± 6.9		39.2 ± 2.3		38.1 ± 2.4		169.4 ± 14.3	a	154.9 ± 8.7	ab	121.9 ± 10.7	b	122.2 ± 7.2		123.5 ± 16.1		127.9 ± 12.2	
P	1568.7 ± 25.6	a	1422.3 ± 33.9	b	1598.4 ± 46.1	a	1502.0 ± 43.9	b	1765.2 ± 60.0	a	1817.5 ± 30.6	a	1408.3 ± 49.7		1491.8 ± 43.2		1512.4 ± 43.4	
K	6553.8 ± 188.3		6585.8 ± 209.4		7243.2 ± 229.8		7071.3 ± 187.7	b	9446.6 ± 414.7	a	10321.4 ± 372.5	a	7302.6 ± 168.9		7789.8 ± 233.6		7822.1 ± 407.8	
Ca	14499.1 ± 608.6		14263.1 ± 1040.8		14253.3 ± 954.6		15566.1 ± 375.2	a	12797.8 ± 623.1	b	11893.9 ± 683.9	b	18297.1 ± 335.5		16200.4 ± 1314.8		15301.6 ± 964.2	
Mn	279.0 ± 11.0		300.2 ± 3.6		282.5 ± 8.5		407.1 ± 46.3		373.1 ± 42.1		342.6 ± 45.7		749.8 ± 49.2		665.5 ± 86.8		751.9 ± 25.0	
Fe	70.4 ± 5.3		63.5 ± 1.6		66.9 ± 1.7		119.4 ± 8.6	a	116.1 ± 7.0	a	90.1 ± 6.2	b	157.1 ± 7.1		155.8 ± 13.1		153.4 ± 7.00	
Cu	9.2 ± 0.4	b	10.1 ± 0.3	b	11.2 ± 0.3	a	17.4 ± 1.1		17.9 ± 1.1		18.5 ± 0.7		18.0 ± 0.7		18.7 ± 0.8		19.5 ± 0.5	
Zn	12.0 ± 0.4		12.2 ± 0.5		13.9 ± 0.8		32.4 ± 2.3	b	47.0 ± 3.3	a	46.7 ± 1.8	a	27.4 ± 1.3		29.6 ± 1.7		37.3 ± 9.9	
N (mg/g)	25.4 ± 3.1		24.0 ± 1.2		23.1 ± 5.8		32.7 ± 1.2		32.4 ± 1.0		32.0 ± 1.4		26.9 ± 0.4		25.7 ± 1.4		25.2 ± 1.0	

Table 5. Precipitation (pp), runoff, soil losses, ammonium-N (NH_4-N), nitrate-N (NO_3-N), phosphate-P (PO_4-P), total N (TN), and dissolved organic carbon (DOC) concentrations and losses in runoff water collected annually in each GMS. There was no recorded runoff in the GC and VS plots during 2010.

Date	GMS treatments	pp (mm)	Runoff (mm)	Soil loss (Kg ha^{-1})	Nutrient concentrations in runoff					Nutrient losses by runoff			
					NH_4-N (mg L^{-1})	NO_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	TN (mg L^{-1})	DOC (mg L^{-1})	Inorganic-N (g ha^{-1})	P (g ha^{-1})	TN (g ha^{-1})	DOC (g ha^{-1})
2008													
7/24	**NE**	16.5	0.74 ± 0.10	1937.2 ± 817.0	0.1 ± 0.0	0.5 ± 0.1	0.2 ± 0.0	1.0 ± 0.1	3.6 ± 0.2	4.9 ± 1.0	2.0 ± 0.3	7.1 ± 3.9	28.1 ± 4.9
8/5	**NE**	32.0	0.89 ± 0.28	1196.5 ± 970.1	0.1 ± 0.0	0.2 ± 0.1	0.2 ± 0.0	0.3 ± 0.1	2.7 ± 0.3	3.4 ± 1.9	1.2 ± 0.9	4.2 ± 2.3	19.3 ± 6.4
8/19	**NE**	70.0	3.01± 0.10	6.6 ± 4.1	0.1 ± 0.0	0.3 ± 0.1	0.2 ± 0.1	0.9 ± 0.3	2.7 ± 0.2	14.0 ± 5.9	9.9 ± 5.4	44.1 ± 28.8	11.9 ± 3.9
Total		118.5	3.64	3140.5						22.3	13.1	55.4	59.3
2009													
6/19	**BS**	36.3	0.05 ± 0.03	2.7 ± 1.5	15.8 ± 7.8	0.6 ± 0.1	1.1 ± 0.6	26.9 ± 7.4	38.1 ± 7.0	7.4 ±3.7	0.5 ± 0.2	10.0 ± 4.0	3.1 ±1.9
	VS		0.02 ± 0.00	0.3 ± 0.1	7.5 ± 4.7	0.5 ± 0.1	1.3 ± 0.5	10.9 ± 5.3	21.2 ± 5.4	1.4 ± 0.6	0.3 ± 0.1	2.2 ± 0.7	1.8 ± 0.6
	GC		0.01 ± 0.00	0.1 ± 0.0	7.4 ± 0.3	2.3 ± 1.4	0.6 ± 0.1	13.8 ± 0.9	28.4 ± 9.5	2.4 ± 1.1	0.1 ± 0.0	3.3 ± 1.1	1.1 ± 0.5
6/28	**BS**	58.9	1.30 ± 0.71	758.8 ± 463.5	0.4 ± 0.1	0.3 ± 0.1	0.6 ± 0.2	5.4 ± 0.9	7.1 ± 0.9	4.6 ± 2.9	6.9 ± 3.8	15.6 ± 8.4	53.1 ± 27.2
	VS		0.16 ± 0.09	3.1 ± 1.9	6.6 ± 1.5	1.7 ± 1.3	1.0 ± 0.3	13.0 ± 5.9	26.9 ± 14.7	1.9 ± 0.5	1.2 ± 0.7	3.3 ± 1.3	21.1 ± 11.9
	GC		0.02 ± 0.00	0.3 ± 0.1	5.1 ± 2.0	0.5 ± 0.2	0.8 ± 0.1	10.7 ± 1.3	28.7 ± 11.5	1.5 ± 0.4	0.2 ± 0.0	2.0 ± 0.3	2.3 ± 0.7
7/23	**BS**	16.1	0.05 ± 0.02	3.7 ± 2.6	0.2 ± 0.0	1.7 ± 0.2	0.5 ± 0.1	10.0 ±3.2	6.9 ± 0.2	0.7 ± 0.2	2.5 ± 0.2	3.5 ± 0.1	52.7 ± 6.4
	VS		0.01 ± 0.00	0.2 ± 0.1	1.7 ± 0.1	0.4 ± 0.0	0.6 ± 0.1	9.5 ± 2.4	13.2 ± 2.3	0.1 ± 0.0	0.4 ± 0.1	1.0 ± 0.3	1.5 ± 0.9
	GC		0.00 ± 0.00	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
8/15	**BS**	36	0.80 ± 0.52	238.4 ± 154.0	0.1 ± 0.0	0.5 ± 0.2	0.4 ± 0.0	1.4 ± 0.3	5.3 ±1.5	2.5 ± 1.3	4.9 ± 2.9	7.7 ±4.5	304.1 ± 277.5
	VS		0.03 ± 0.02	0.7 ± 0.2	0.4 ± 0.1	0.3 ± 0.0	0.3 ± 0.0	1.5 ±0.1	7.5 ± 0.2	0.1 ± 0.0	0.2 ± 0.0	0.8 ± 0.2	28.9 ± 0.4
	GC		0.00 ± 0.00	- -	- -	- -	- -	- -	- -	- -	- -		

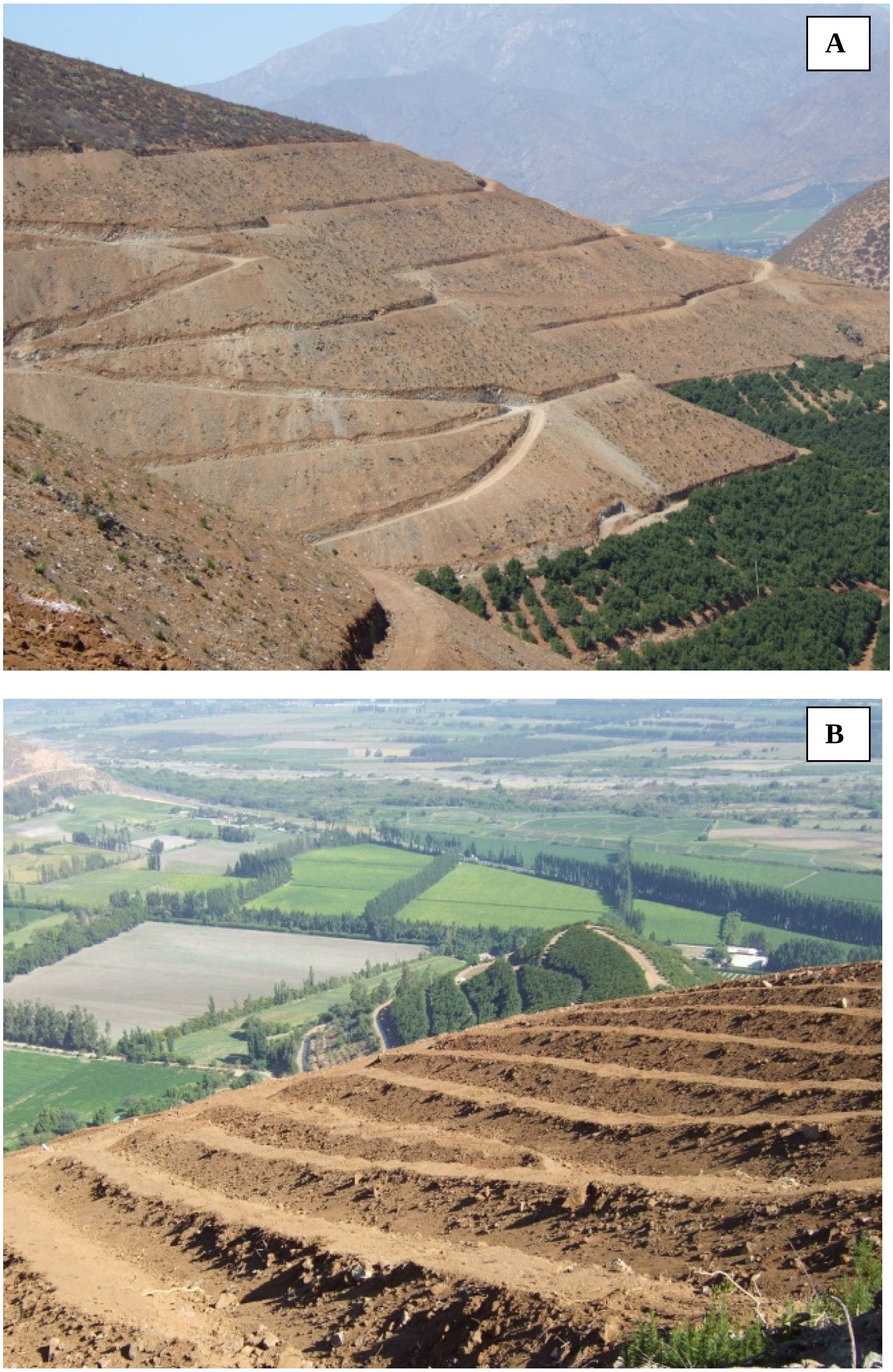
8/19	**BS**	34.7	1.04 ± 0.60	30.5 ± 18.1	0.03 ± 0.0	0.2 ± 0.0	0.3 ± 0.0	0.7 ± 0.0	4.0 ± 0.3	4.0 ± 1.9	5.1 ± 1.5	5.5 ± 2.9	224.0 ± 114.3
	VS		0.04 ± 0.02	0.9 ± 0.6	0.03 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.6 ± 0.2	4.7 ± 0.7	0.5 ± 0.1	0.2 ± 0.0	0.4 ± 0.1	30.3 ± 15.2
	GC		0.00 ± 0.00	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
Total	**BS**	182	3.24	1034.1						19.2	19.9	42.3	637.0
	VS		0.26	4.5						4.0	2.3	7.7	83.6
	GC		0.03	0.4						3.9	0.3	5.3	3.4
2010													
6/18	**BS**	53.5	1.00 ± 0.07	214.1 ± 13.0	0.1 ± 0.0	0.1 ± 0.0	0.4 ± 0.0	0.8 ± 0.4	5.7 ± 1.9	4.0 ± 2.6	5.3 ± 3.4	12.5 ± 6.1	48.6 ± 5.6
6/24	**BS**	108.7	1.30 ± 0.08	1769.7 ± 98.4	0.2 ± 0.0	0.3 ± 0.0	0.2 ± 0.0	0.8 ± 0.1	3.6 ± 0.5	15.3 ± 4.9	6.7 ± 0.8	26.5 ± 7.9	208.8 ± 29.6
7/6	**BS**	32.1	2.03 ± 0.28	1459.4 ± 895.8	0.3 ± 0.1	0.4 ± 0.1	0.5 ± 0.0	1.3 ± 0.4	4.9 ± 1.0	16.2 ± 7.8	12.3 ± 5.2	28.5 ± 13.5	87.2 ± 55.99
Total		194.3	4.33	3443.2						35.5	24.3	67.5	344.6

Table 6. Means and standard errors for soil bulk density (g/cc), macro/meso/micro/porosity (%), available water capacity (AWC), and aggregate stability (%). Data were analyzed using a repeated measurement model, accounting for the overall effect of treatments throughout the three-year study. When significant main effects were indicated among treatments, means were separated using Tukey's HSD test (different letters indicate significant differences at ** = *P* ≤0.05, or * = *P* ≤0.1 for BS, VS and GC treatments; ns= No significant differences.

	2009			**2010**			**2011**			Tukey's *HSD*		
	BS	**VS**	**GC**	**BS**	**VS**	**GC**	**BS**	**VS**	**GC**	**BS**	**VS**	**GC**
Bulk Density	1.34 ± 0.04	1.31 ± 0.08	1.20 ± 0.07	1.38 ± 0.06	1.32 ± 0.05	1.31 ± 0.04	1.35 ± 0.05	1.33 ± 0.01	1.26 ± 0.07	a	ab	b*
Macroporosity	4.47 ± 0.59	4.74 ± 0.78	6.33 ± 0.37	3.26 ± 0.31	2.99 ± 0.58	4.68 ± 0.31	2.83 ± 0.30	3.03 ± 0.57	3.86 ± 0.59	b	b	a**
Mesoporosity	20.36 ± 0.77	22.90 ± 0.74	21.33 ± 1.56	22.82 ± 0.50	25.15 ± 1.85	21.61 ± 1.12	26.28 ± 0.95	26.20 ± 1.74	28.25 ± 1.20		ns	
Microporosity	8.86 ± 0.35	5.89 ± 1.45	7.45 ± 0.69	14.17 ± 0.44	12.15 ± 0.64	13.77 ± 0.85	13.56 ± 0.71	14.64 ± 1.21	12.50 ± 1.31		ns	
AWC	8.19 ± 0.27	6.44 ± .28	8.78 ± 0.83	10.73 ± 0.23	10.85 ± 0.04	12.05 ± 0.20	12.98 ± 0.77	12.99 ± 0.67	13.14 ± 0.97	ab	b	a**
Aggregate Stability	24.82 ± 2.28	23.80 ± 1.96	37.38 ± 5.75	21.86 ± 3.04	21.66 ± 2.42	32.18 ± 5.78	29.30 ± 0.87	38.95 ± 2.28	38.68 ± 2.65	b	b	a**

Table 7. Effects of GMSs treatments on soil nutrient concentrations (mg/kg), organic matter (%), total C and N (mg/g), C-to-N ratios, and pH. Values are means ± SEM of five replicates. Data were analyzed using a repeated measurement model, accounting for treatment main effects spanning the three years. When differences were indicated, treatment means were separated using Tukey's HSD test. Different letters for each row indicate significant main effect differences at ** = *P* ≤0.05, or * = *P* ≤0.1, or NS = no significant differences among BS, VS and GC treatments.

Variable	2009			2010			2011			HSD test		
	BS	**VS**	**GC**	**BS**	**VS**	**GC**	**BS**	**VS**	**GC**	**BS**	**VS**	**GC**
P	9.1±0.7	8.1±1.0	11.1±3.2	9.2±1.0	9.5±2.3	15.0±2.9	9.9±0.8	10.5±1.5	12.2±2.1	*ab*	*b*	*a**
K	121.7±15.7	157.2±19.8	196.5±28.6	99.5±32.9	111.61±5.1	161.9±16.5	110.7±18.8	121.8±11.5	167.6±17.9	*b*	*b*	*a***
Mg	540.4±49.2	670.7±98.9	700.3±94.3	569.46±39.0	702.4±80.0	725.8±70.4	557.9±43.3	619.5±88.2	651.1±77.9	*b*	*a*	*a***
Ca	2168.6±13.2	2374.5±172.8	2397.5±226.6	3340.7±113.2	3193.7±132.4	4157.9±933.5	3336.8±42.4	3346.1±103.2	3049.4±137.3		*NS*	
Fe	0.5±0.1	0.4±0.1	0.5±0.1	0.1±0.1	0.5±0.2	0.4±0.5	0.3±0.0	0.4±0.0	0.5±0.0		*NS*	
Al	12.7±0.4	15.1±1.4	13.8±2.1	13.9±0.7	13.3±1.6	12.5±1.6	13.9±0.9	14.0±1.5	12.4±1.5		*NS*	
Mn	29.4±3.1	48.2±5.8	47.8±7.1	11.0±5.6	8.8±1.9	14.9±3.1	46.9±5.1	34.5±9.5	28.6±2.6		*NS*	
Zn	1.3±0.1	1.2±0.1	1.3±0.2	40.9±14.5	9.9±4.0	9.5±3.4	15.0±4.0	10.8±1.6	7.7±1.9	*a*	*b*	*b***
Cu	2.8±0.5	2.3±0.4	3.9±0.2	7.4±0.6	7.3±0.6	7.0±0.4	7.4±0.3	7.4±0.5	7.1±0.4	*ab*	*b*	*a***
pH	6.6±0.1	6.8±0.1	7.2±0.1	6.6±0.2	6.5±0.1	6.8±0.2	6.9±0.1	6.9±0.1	7.0±0.1	*b*	*b*	*a***
O.M.	2.1±0.1	2.5±0.2	2.8±0.2	2.1±0.1	2.5±0.1	2.6±0.1	2.2±0.1	2.6±0.2	2.7±0.2	*c*	*b*	*a***
NO_3^-	8.0±1.6	3.8±0.9	11.2±3.8	66.6±9.4	50.6±5.4	58.7±4.3	32.2±9.1	33.5±8.5	25.1±2.9		*NS*	
C	9.0±0.8	10.5±1.4	11.6±1.2	6.1±0.5	7.4±0.6	9.2±0.5	7.0±0.9	8.7±0.5	11.5±1.3	*c*	*b*	*a*
N	0.9±0.0	1.0±0.1	1.1±0.1	0.8±0.0	0.9±0.0	1.0±0.1	0.8±0.1	0.9±0.0	1.0±0.1	*b*	*b*	*a*
C/N	9.5±0.6	10.3±0.7	10.4±0.7	7.4±0.5	8.7±0.6	9.3±0.2	8.3±0.7	9.5±0.5	10.9±0.8	*b*	*a*	*a*



Figures 1A- Hillside after the removal of native vegetation;
1B- Raised berms parallel to the slope, prior to planting avocados.

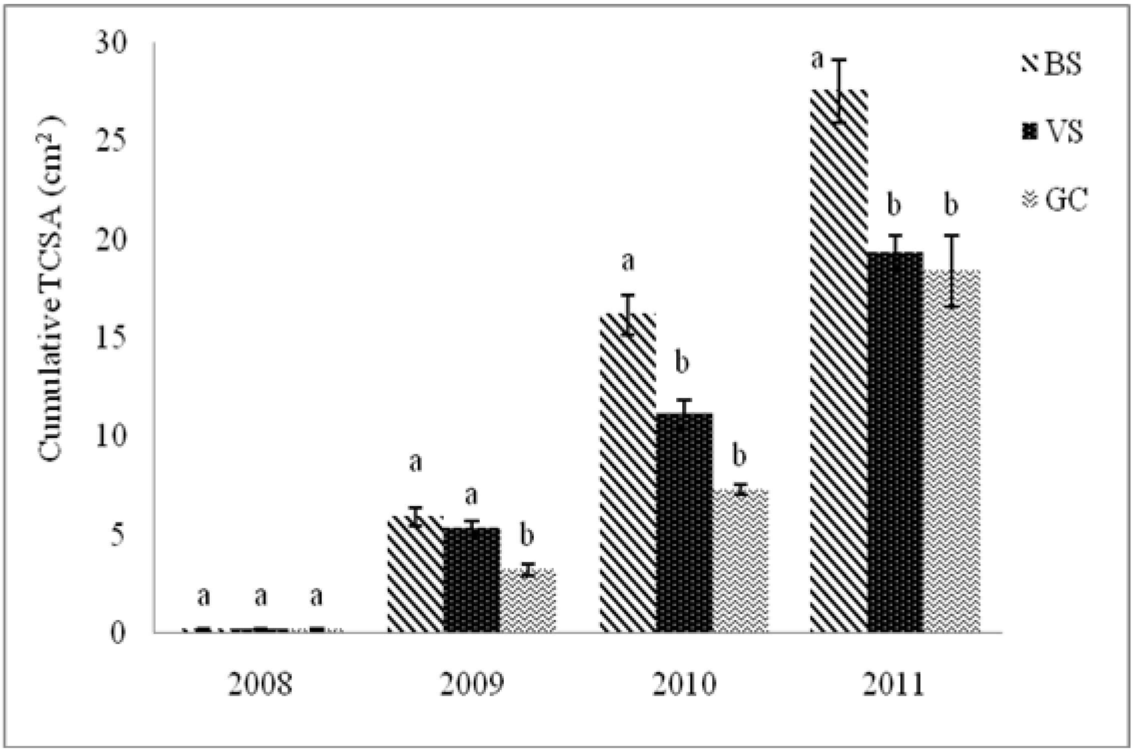


Figure 2. Cumulative mean tree Trunk Cross Sectional Area (TCSA) (cm²) from 2008 through 2011. Letters of mean separation were generated from Tukey's HSD test at *P*≤ 0.05.

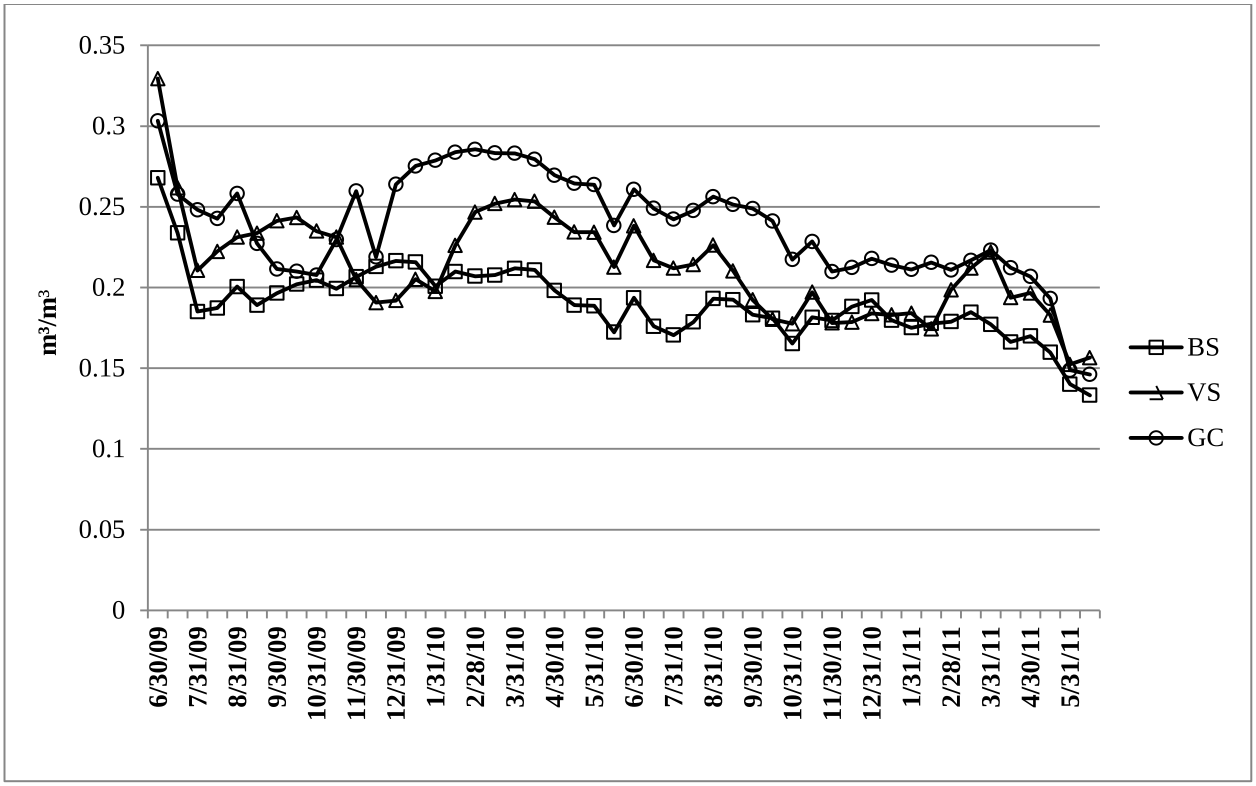


Figure 3. Volumetric soil water moisture content (m^3 m^{-3}) under different GMS treatments. Measurements were taken every 2 hr for 104 weeks from 2009 to 2011. Values presented in the figure are averages of biweekly data for each treatment. *P*< 0.0001 for main effect of treatment over time.

CHAPTER FOUR:

ROOT DISTRIBUTION AND DEMOGRAPHY IN AN AVOCADO ORCHARD UNDER DIFFERENT GROUNDCOVER MANAGEMENT SYSTEMS

4.1 Introduction

Competitive traits of plants living in mixed communities are one of the main factors influencing plant performance. Below-ground competition for resources (i.e. nutrients and water) and non-resource (i.e. interference competition for space) factors can cause diverse responses, including physiological, morphological, developmental or growth effects (Schenk, 2006). The capacity of plants to adjust their form and function to environmental stresses is a phenomenon known as plasticity (Sultan, 2000). For instance, shifts in functional traits such as specific root length, nutrient uptake rate or biomass allocation to roots in response to variable resource levels in the soil, may allow an individual to succeed in contrasting environments. Root plasticity is an important characteristic of plants that allows them to mitigate intra- and inter-specific competition, by limiting the overlap of individuals' root systems (Schiffers et al., 2011). Several literature reviews have compiled the multiple studies on root competition and interactions in forest, woodlands and agroforestry systems (Schenk et al., 1999; Casper and Jackson, 1997; Nambiar and Sands, 1993; Schroth, 1998; Coomes and Grubb, 2000); however there are only a few such studies involving perennial fruit tree root systems.

Several studies have shown the effects of groundcover management systems (GMSs) on aboveground tree growth and yields (Merwin and Stiles, 1994; Sanchez et al., 2003; Neilsen et al., 2003; Faber et al., 2001). However, only a few studies have investigated the influence of GMSs on root growth or demography. Research in grapevines, apple (Malus X sylvestris Mill.) and peach (Prunus persica Batsch) trees (Yao et al., 2009; Morlat and Jacquet, 2003; Parker and Meyer, 1996) demonstrated considerable decrease in the total number of roots of these fruit-crops when they were grown in mixtures with groundcover vegetation, compared with vegetation-free plots, suggesting that resource competition negatively affected the performance of the fruit crop. Research on the vertical root distribution of fruit trees grown in different GMSs has shown more and deeper root proliferation for trees under groundcover vegetation, compared to those grown in bare soil (Atkinson 1980; Yao et al. Atkinson and White, 1976; 2009; Celette et al., 2005; Morlat and Jacquet, 2003). Elimination of tree-row vegetation with herbicides prevents competition from other species roots, and presumably allows tree roots to grow near the soil surface (Haynes, 1980; Tworkoski and Glenn, 2001).

Positive and negative interactions between plants are stronger in resource-poor than in resource-rich environments (Goldberg et al., 1999), and root competition is reportedly more intense in environments with limited resources (Pugnaire and Luque, 2001). Glenn and Welker (1993) reported a reduction in root competition between peach trees and tall fescue (Festuca arundinaceae) when irrigation was provided, and minimal effects of cover crops on root growth of macadamia nut trees (Macadamia tetraphylla Johnson) were reported in a high rainfall area of subtropical Australia (Firth et al., 2003). Water and nutrient uptake in trees occurs primarily in fine unsuberized “feeder” roots (Bauhus and Messier, 1999; Bolte and Villanueva, 2006; Richards et al., 2010). Fine root lifespans are influenced by endogenous factors such as root order, diameter, and mycorrhizal associations, as well as exogenous factors such as soil temperature, moisture, and nutrient availability (Eissenstat and Yanai, 1997; Guo et al., 2008). GMSs can also have significant effects on exogenous factors controlling fine root lifespan (Atucha et al., 2011; Sanchez et al., 2007; St. Laurent et al., 2008) and consequently affect tree and root performance.

Little research has been reported on avocado (Persea americana Mill.) root systems in different management systems, soils, or climate zones. The present study involved minirhizotron observations of root demography and distribution in a newly planted avocado orchard established on a steep hillside in central Chile, to investigate whether different GMSs affect avocado tree performance and environmental externalities. We tested the general hypothesis that avocado root phenology, production, morphology, vertical distribution, and lifespan are affected by GMS treatments. More specifically, we hypothesized that avocado tree roots are negatively affected by below-ground interspecific competition from groundcover species planted to minimize soil erosion and runoff.

4.2 Materials and Methods

Orchard site and GMS treatments.

The experimental site is a 0.75 ha plot with 47% slope located at the edge of a 300 ha hillside avocado orchard in Panquehue, central Chile (Latitude 32^{0}.49’25.94’’ S, Longitude 70^{0}55’56.04’’ W). The soil type at this site is Andisols, based upon textural ratios determined by fractional sedimentation (Table 1). As typical for new hillside avocado orchards in this region, the site was prepared for planting in 2007 by removing all native vegetation from the steep slopes with an excavator. Berms approximately 50-m long and 1-m high were constructed in Dec. 2007, gathering the soil from the inter-rows into raised berms for the planting rows (Fig. 1). Avocado trees (‘Hass’ on ‘Mexicola’ seedling rootstocks) were planted on the berm-rows in Aug. 2008, at 2 x 5 m spacing.

During the first year after tree establishment (Aug. 2008 to Aug. 2009) an irrigation system was installed, consisting of one microsprinkler line per berm-row with one sprinkler per tree, capable of providing 20 L hr-1 irrigation. In Aug. 2009 the microsprinkler system on the berm-rows was changed to two trickle emitters per tree, delivering 4 L hr-1. Another line of microsprinklers provided 34 L hr-1 irrigation in the ditches between berms, facilitating the establishment of seeded groundcover vegetation; these microsprinklers were removed after the groundcovers were fully established in Dec. 2008. Three GMS treatments were established in Aug. 2008, in a complete randomized block design with five blocks and one replicate of each GMS per block, and maintained as follows. Treatment 1: Bare soil (BS)—a combination of two herbicides (glyphosate and terbuthylazine) was applied on the entire plot surface (to both berms and ditches), at 1.4 and 3.0 kg active ingredient (a.i) ha-1, respectively. Terbuthylazine was applied in these plots Aug. 2008, June 2009, and May 2010 and 2011, and glyphosate applied Aug. 2008 and 2009, June 2010 and Feb. 2011 as needed to maintain weed-free treatment plots. Treatment 2:

Vegetation strip (VS)—a post-emergence herbicide treatment consisting of glyphosate was applied on a 1-m-wide strip on the tree-row berm at a rate of 1.4 kg a.i. ha-1 in Aug. 2008 and 2009, May 2010, and Feb. 2011, to suppress weeds during the rainy season. In Aug. 2008 a mixture of ryegrass (Lolium rigidum var. wimmera) and Hualputra (Medicago polymorpha sp.) was seeded in the ditches between the tree berm-rows, at a rate of 18 and 12 kg ha-1, respectively. During Oct. 2009 and 2010 this groundcover mixture was suppressed with a contact herbicide (paraquat) applied at a rate of 0.9 L a.i. ha-1. During Feb. 2010 the groundcover was mowed to a 10-cm height using rotary scythes to prevent possible fires during the summer. Treatment 3: Groundcover (GC)—The same mixture of ryegrass (Lolium rigidum var. wimmera) and Hualputra (Medicago polymorpha sp.) as in VS treatment was established in Aug. 2008, covering the entire surface of the plots (berm-row and lane-ditch), and mowed to a 10-cm height during Feb. 2009 and 2010.

Minirhizotron tube installation and image observation.

During the winter season in Aug. 2008 as the trees were planted, we selected one tree site in the center of each GMS plot for root study. During the planting operation, two transparent polycarbonate minirhizotron (MR) observation tubes of 0.05-m diameter were placed diagonally into the excavated tree-planting hole on either side of the tree location, 0.4 m from the trunk and approximately parallel to the tree row. The tubes were placed at 30^0 and 60^0 angles from the horizontal, and were 0.9 and 1.5 m long, respectively, of which 0.5 and 0.9 m of soil depth were accessible using the minirhizotron camera (Fig. 1). A third tube was installed in the tree row 0.4 m from the tree trunk and perpendicular to the horizontal, extending to a depth of 0.5 m. To allow time for tree root establishment after transplanting, no images were recorded until the following year. Root images were then recorded monthly from Aug. 2009 to June 2010, bi-monthly from Sep. 2010 to March 2011, and in June and November of 2011, with a minirhizotron digital video camera Model BTC-ICAP (Bartz Tech. Co, Santa Barbara, CA).

Root observation and measurements.

The number, location, depth, diameter, and date of first appearance and disappearance of all roots in each tube were recorded with WinRhizoTron MF (Regents Inc. Quebec, Canada). Root birth was estimated by extrapolating back to a date midway between the first observation date for each root and the previous recorded observation date. Roots were considered dead when they became black and shriveled (Comas et al., 2000), or if a root disappeared from a viewing location and did not reappear. Root diameter was measured at the time of root birth. Total number of newly emerged roots for each date, root distribution at each depth interval, root diameter, and median root lifespan (time elapsed when 50% of roots from an initial cohort had died or disappeared) were recorded for each season and year.

To estimate the number of new roots per tree over time, data were aggregated by regional season and annual growing cycle. Year one (2009-2010) included observations from Aug 2009 to June 2010; year two (2010-2011) included observations recorded from Sept. 2010 to Nov. 2011. In accordance with the climate of this southern hemisphere region, observations during the months of September through November were considered as “spring”; December through March were considered “summer;” and April through June were considered “fall.” No root observations were recorded during the mid-winter months (July and August) because access to trees with the MR unit was too difficult on the steep and slippery slopes of this orchard during heavy precipitation periods.

Avocado trees were irrigated intermittently, when tensiometer readings at the site exceeded -75 kPa, due to below-average precipitation for this region. Cumulative precipitation during 2008 was 120 mm, with three precipitation events during July and August; 185 mm in 2009, with five precipitation events from June to August; and 195 mm in 2010, with three precipitation events during June and July. The soil chemical, physical and hydraulic conditions in this experimental orchard have been reported elsewhere (Atucha, 2012, chapter 3).

To facilitate comparisons of treatment effects on root distribution in the soil profile, data were pooled into three soil-depth intervals for statistical analyses (0-0.3, 0.3-0.6, and 0.6-0.9 m). Although there were three tubes beneath each tree, only observations from the 1.5-m long 30○ angle tubes under each tree were used for root depth-distribution comparisons.

After analyzing the statistical distribution of root diameters, we parsed the root diameter data into two root categories—roots < 0.2-mm diameter, and roots ≥ 0.2-mm diameter. For significance tests of observed differences in root diameter among the GMS treatments, data from all three tubes per tree were pooled.

Data analysis

Root counts over time were analyzed as a repeated measures analysis of variance model at P= 0.05, and data were log-transformed to satisfy the model assumptions. Comparisons among treatments within soil-depth intervals and root-diameter categories were evaluated using a one-way analysis of variance for a randomized complete block design at P= 0.05 or 0.1, as noted. Root survivorship and lifespan estimates were calculated using the Kaplan-Meier survival model (Kaplan and Meier, 1958), for each season during the 2009-to-2010 growth period. To test the covariate effects on root lifespan, Cox proportional hazards regression analyses (Cox, 1972) were run on pooled data from the first year of observations (Sep 2009 to June 2010), with the following variables as covariates: treatment, season of birth, root diameter at appearance and depth in the soil (Table 1). In addition, Cox proportional hazards regression models were calculated for roots <0.2 mm diameter, controlling for treatment, season of root emergence, and depth in the soil (Table 2).

Cox proportional hazard regression allows determination of the “mortality hazard” of an individual covariate when the influence of all other covariates is held constant. The hazard represents the mortality rate for a root at time t, where t is the product of a baseline hazard function of k covariates (Allison, 2010). A negative parameter estimate indicates a decreased rate of mortality with an increase in a given covariate; a positive parameter estimate indicates an increased rate of mortality with an increase in that covariate (Wells and Eissenstat, 2001). For a categorical variable such as season, which could have only three nominal values in our observations (spring, summer and fall), the hazard ratio can be interpreted as the ratio of hazard for a root born in spring or summer vs. that of a root born in fall—while controlling for all other covariates. These statistical analyses were performed using JMP software (JMP, Version 9; SAS Institute Inc., Cary, N.C., U.S.)

4.3 Results

New root counts

The full analysis of variance indicated no significant GMS treatment effects on the number of new roots per tree (P=0.714). However, when data were combined across treatments, the number of new roots per tree was greater when trees were non-bearing in 2009-2010, compared with 2010-2011 when they were carrying their first crop (P=0.002). The number of newly emergent roots was significantly greater in Spring and Summer than in Fall during 2009-2010, but not during 2010-2011 (P=0.016, Fig.2 A-B). There were no significant interactions for emergent root counts between year and season.

Root depth distribution

Root counts at different depth intervals differed among treatments (P=0.0457) (Fig. 3). In the upper 0.3 m of soil, trees in BS plots had more roots than those in VS and GC treatments. At mid-depth (0.3-0.6 m) in the soil profile, trees in the BS plots had fewer roots than those in VS and GC plots. In the deepest soil-depth interval (0.6-0.9 m), trees in BS plots had more roots than those in the other two treatments.

Root diameter

When all root observations were pooled, there were significant differences in root diameter among the GMS treatments (P=0.0490) (Fig. 4). Trees in BS plots had more roots within the ≥0.2 mm diameter class than trees in VS and GC plots, but trees in GC had more roots <0.2 mm diameter than trees in BS plots. Within the <0.2-mm-diameter root cohort, the GC trees had 7-fold and 2-fold more roots < 0.1 mm diameter than the BS and VS trees, respectively.

Factors influencing root lifespan

Root diameter at first appearance, root distribution in the soil profile, and season of root birth had significant effects on root lifespan (Table 1). The lifespans of roots ≥ 0.2 mm diameter were 52% longer than those of roots <0.2 mm diameter (Table 1, Fig. 5). Compared with roots in the uppermost soil profile (0-30 cm), the lifespans of roots in the 31-to-50 cm and 51-to-90 cm depth intervals were 51 and 49% greater, respectively (Table 1, Fig. 6). The lifespans of roots emerging in fall were 54 and 57% greater than those of roots emerging during summer and spring, respectively (Table 1, Fig.7). Groundcover treatments did not consistently influence root lifespan (P >0.5). However, when roots <0.2 mm diameter were considered separately, the season of emergence, soil depth, and GMS treatments all influenced their root lifespans (Table 2). The influence of emergence time and soil depth on survival of roots <0.2 mm diameter was similar to that on roots in other diameter categories (Table 1). Compared with the GC plots, the lifespans of roots <0.2 mm in the BS and VS plots were 61% and 47% greater, respectively (Table 2).

4.4 Discussion

Patterns of root production

Crop load and root growth are thought to compete for plant carbohydrates (Hansen, 1977), and heavy fruit loads reportedly suppress concurrent root growth in apple (Malus X sylvestris Mill.), peach (Prunus persica L.), pistachio (Pistacio vera L.) and macadamia (Macadamia tetraphylla Johnson) (Chen et al., 1997; Rosecrance et al., 1996; Inglese et al., 2002; Firth et al., 2003). In our study, competing fruit load decreased new root emergence during the trees’ first bearing year (2010-2011), compared to the previous year (2009-2010). During that nonbearing year more new roots emerged in the spring and summer months compared to fall months; however, during the bearing year there were no differences for root emergence among the seasons (Fig. 2A-B). Moreover, fewer roots emerged in spring of the bearing year than in spring of the nonbearing year (P=0.042), suggesting greater carbohydrate limitation during the spring of the bearing year. Competition for resources between concurrently developing spring shoots and newly set fruit in avocado is well documented, and thought to be responsible for high percentages of flower and fruitlet abscission in this species (Scholefield et al., 1985; Cutting and Bower, 1990; Finazzo et al., 1994). Our observations suggest that carbon limitation had similarly negative impacts on root growth of young avocado trees, in contrast with the report of Robinson et al. (2002) that crop load of six-year-old avocado tree had no effects on root growth patterns in California.

Season of root emergence influenced root lifespan during the nonbearing year in our study (Table 1 and 2). Higher soil temperatures during spring and summer, in addition to competition with above-ground growth, may increase metabolic activity of roots born in summer and spring, and consequently shorten their lifespan (Eissenstat et al., 2000; Huang et al., 2005; Anderson et al., 2003). Alternatively, during mid and late fall in the Mediterranean-type climate of central Chile, evergreen avocado trees are still actively photosynthesizing but there is minimal shoot growth. These fall conditions could allow more allocation of photoassimilates into relatively fewer new roots that have longer lifespans than those born during spring and summer.

Root distribution in the soil profile

Previous researchers have reported that fruit trees in weed-free plots have more roots than those in weedy plots (Atkinson and White, 1976; Parker and Meyer, 1996; Yao et al., 2009). Even though we observed no statistical differences in the number of roots per tree among different GMSs treatments, the avocado roots exhibited different vertical distributions when grown with or without groundcover vegetation (Fig. 3). As previously reported in other GMS studies (Yao et al., 2009; Tworkoski and Glenn, 2001; Parker et al., 1993), competition between trees and groundcovers for water and nutrients may cause fruit-tree roots to proliferate deeper in the soil profile. This might explain the greater number of avocado roots at 31-50 cm soil depth under GC, compared with BS plots. However, during the entire course of this study we observed no significant GMS-related differences in avocado leaf nutrient content, and soil nutrient availability and water content were actually greater in GC than in BS plots (data presented in chapter 3). These observations suggest that trees in the BS plots were not stressed by nutrient or water deficiencies, and that other factors led to observed differences in tree root counts at various depths under these GMSs.

As reported in many previous studies (Callaway et al., 1991; Dudley and File, 2007; O'Brien and Brown, 2008; Messier et al., 2009) the fine roots of trees can be negatively affected by roots of other species through resource (nutrients and water) and non-resource competition (interference for space). Although there were no differences in avocado leaf nutrient content among the GMSs, and trees were irrigated and fertilized throughout this study, asymmetries in root distribution of avocado trees under different GMSs cannot be conclusively attributed to non-resource spatial competition, because we did not analyze for nutrient differences in the root systems of trees. An alternative explanation could be that avocado trees in GC plots experienced both resource and spatial competition when the groundcovers and trees were establishing, resulting in smaller trees in GC compared with BS plots (data presented in chapter 3). That initial resource competition would have diminished subsequently with irrigation and fertilization, and proliferation of avocado roots into deeper soil where groundcover roots were not present. A similar spatial segregation of root systems was reported by Schenk et al. (1999), and suggests considerable morphological plasticity of avocado root systems under different GMSs.

Water and nutrient uptake by roots is based on root length and/or root surface area rather than just root mass (Molz, 1981; Nye and Tinker, 1977). Specific root length (SRL) is the length-to-mass ratio of a root segment, and has been suggested as a morphological indicator that represents “economic” traits of root production and maintenance (Ostonen et al., 2007). Higher SRL is associated with smaller diameter roots, and if fewer resources are invested in roots with smaller biomass but higher SRL, those roots presumably “cost” less to the plant and are more cost-efficient for absorbing water and nutrients than roots of larger diameter (Eissenstat, 1992). Although we did not measure SRL of avocado trees, our results show that trees in both the GC and VS groundcover plots exhibited more small diameter roots than trees in the BS plots (Fig. 4). This suggests higher avocado SRLs in the two treatments with vegetative groundcover compared with roots in the BS treatment, and indicates that avocado trees in groundcover plots may have optimized their nutrient and water uptake by producing a higher number of less "expensive" and more efficient roots than trees in BS plots. On the contrary, trees in BS plots would have experienced negligible groundcover competition, and they exhibited root distribution patterns previously observed for avocados in their native habitat. Scora et al. (2002) reported abundant surface feeder roots in natural avocado stands, describing them as "litter feeder" roots because of their large diameter (> 1 mm) and abundance in the rich surface organic litter of native tree stands. Avocado root systems were reported to be relatively shallow, with few roots deeper than 1 m (Wolstenholme, 2002) in well drained and aerated soils, comparable to conditions in the newly constructed berms of our study. These root traits would explain why we observed many tree roots below 50 cm in the soil profile under all GMS treatments. The uniquely mounded soil profiles and constructed berms of our study may also have influenced root distribution, because roots that were more than 50 cm below the tree base were often closer than 50 cm to the lateral flanks of those berms. In other words, some of the deeper roots in observation tubes may have comprised an umbrella shaped root system when viewed radially across the berm profile (see Fig. 1).

Factors affecting root mortality

Roots located deeper in the soil had lower mortality risk (Table 3, Fig. 3). Root longevity has been positively correlated with soil depth in fruit trees and grapevines (Anderson et al., 2003; Kosola et al., 1995; Wells et al., 2002; Comas et al., 2010), in contrast to reports for sugar maple (Acer saccharum Marshall) and longleaf pine (Pinus palustris Mill.) (Hendrick and Pregitzer, 1993; Guo et al., 2008). It is unclear why depth should have a positive effect on root lifespan, but roots deeper in the profile may experience less variation in temperature and water availability (Hendrick and Pregitzer, 1993; Wells et al., 2002), as well as reduced pathogen and herbivore pressure (Eissenstat and Yanai, 1997). Even though our avocado trees were irrigated more-or-less year-round, the exposed soil surface throughout BS treatments, and on the berm surface beneath trees in VS plots, may have reduced root survivorship due to more pronounced heating and drying cycles in the exposed upper soil layer. The hot, dry summers and intense sunlight at our site could also have shortened lifespans of superficial roots in the BS and VS treatments.

Several studies have shown positive correlations between root diameter and lifespan in fruit trees (Wells and Eissenstat, 2001; Baddeley and Watson, 2005; Wells et al., 2002), while others have shown that root order or branching are stronger predictors of root lifespan than diameter (Guo et al., 2008). It is often not possible to determine root order through the limited viewing area of minirhizotron tubes, and we can therefore make no inferences about branching order in relation to root mortality. However, smaller diameter roots had shorter lifespans (Table 1), and those in BS plots had a lower mortality risk than those in GC plots (Table 2). Smaller diameter roots reportedly have greater surface area, higher nitrogen concentrations (Pregitzer et al., 2002), and lower structural carbon content (Guo et al., 2004)—traits that presumably increase their respiration rates compared with larger diameter roots (Pregitzer et al., 1998). These attributes are likely to increase root mortality for smaller diameter roots (Wells and Eissenstat, 2001) compared with larger diameter roots. When we subdivided roots <0.2 mm into groups with diameters of 0-0.1 mm, 0.11-0.15 mm, and 0.16-0.2 mm, the trees in GC plots had more roots in these smaller diameter categories than trees in BS plots. Wells and Eissenstat (2001) reported differences in lifespan of roots correlating with 0.1-mm-diameter increments for apple trees, and it appears that the finer diameter avocado roots exhibited similar lifespan differences related to GMS treatments in our study.

Growing conditions of avocado trees in a commercial hillside orchard in the Mediterranean climate of central Chile differ substantially from their native habitat in the fertile and humid upland and lowland forests of Mexico and Central America. The preponderance of deeper and thinner roots reflects considerable morphological plasticity of avocado root systems that help them to buffer resource and non-resource competition when grown in mixed species stands. The adaptive response of growing less expensive and more efficient roots, with the tradeoff of a shorter lifespan, reflects avocado trees’ ability to adapt to diverse and challenging growing conditions over a wide range of soil and climate regimes.

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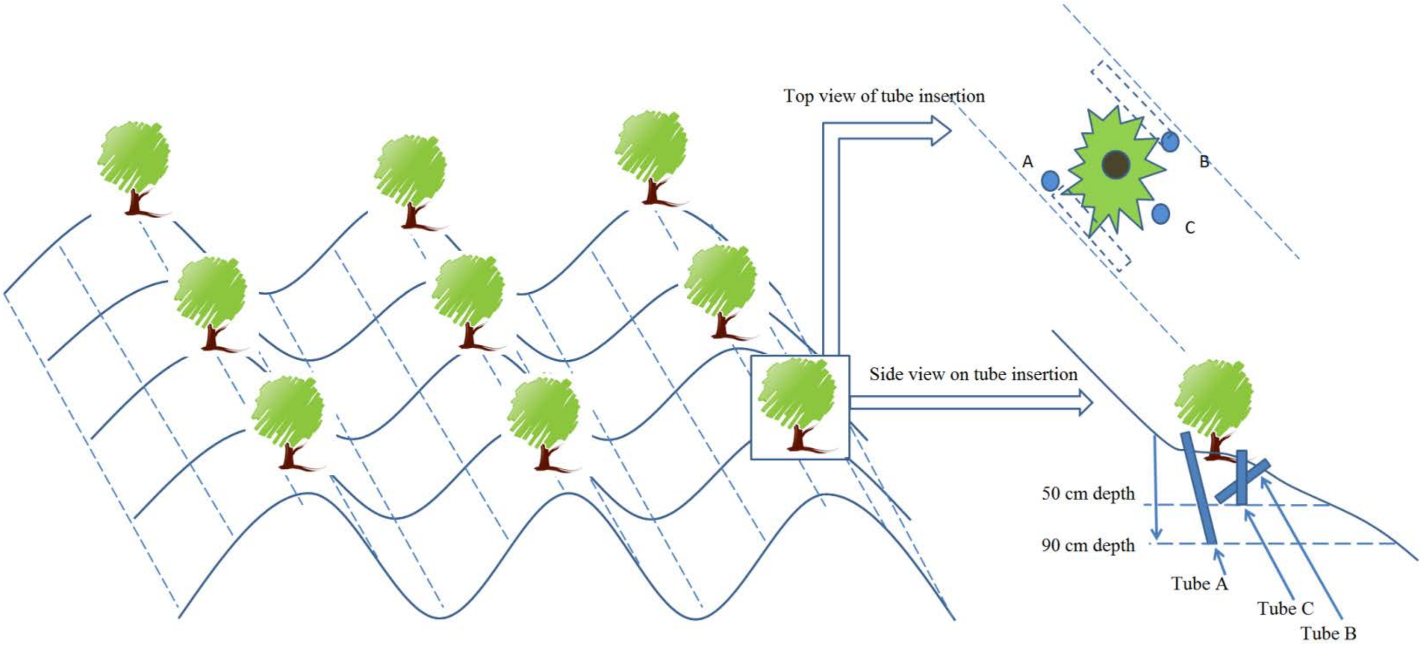

Figure 1. Top and side views of tube locations, length and depth below ground for a root observation study, in a hillside orchard with raised berms parallel to the slope.

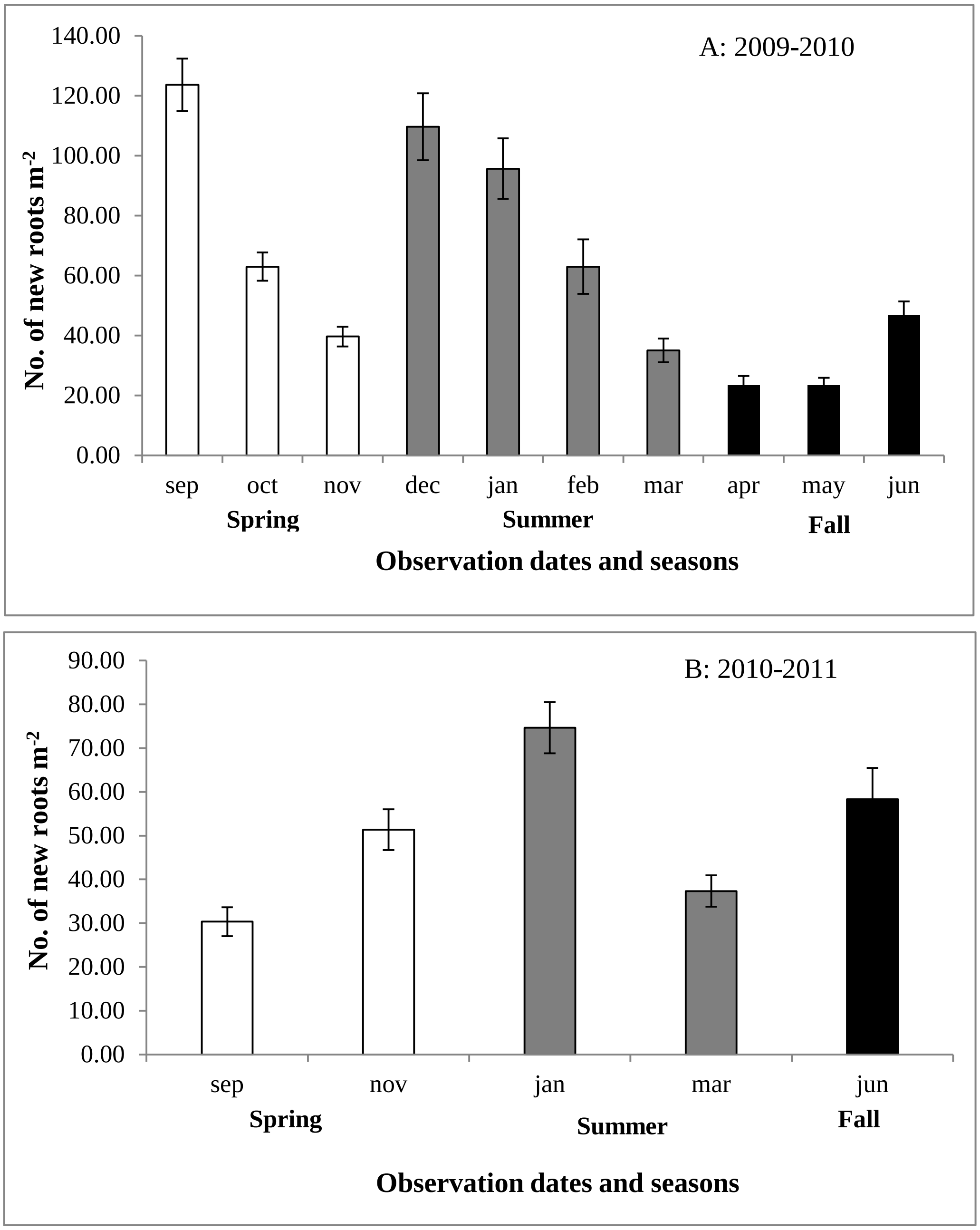

Figure 2A-B. Number of new avocado roots observed during 2009-2010 and 2010-2011. Bars in color white, gray and black represent spring, summer and fall months, respectively. The numbers of new roots per year and season were analyzed using a repeated measures analysis of variance. Error bars are standard error of mean for n=15.

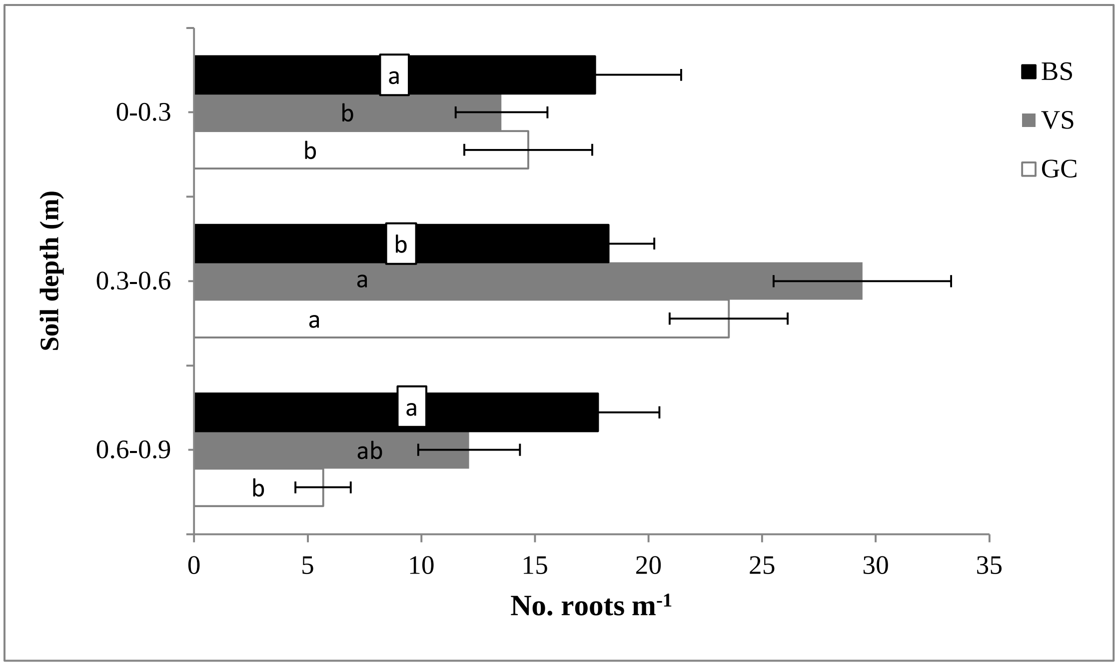

Figure 3. Depth distribution of avocado roots at 0-0.3; 0.31-0.6 and 0.61-0.9 m for treatments BS (Bare Soil), VS (Vegetation Strip) and GC (Ground Cover) during the entire study period. Values are the average of 5 replicates for each treatment, ± standard error of the mean. The asterisks indicate significant differences among treatments (*P*=0.05) within each depth interval.

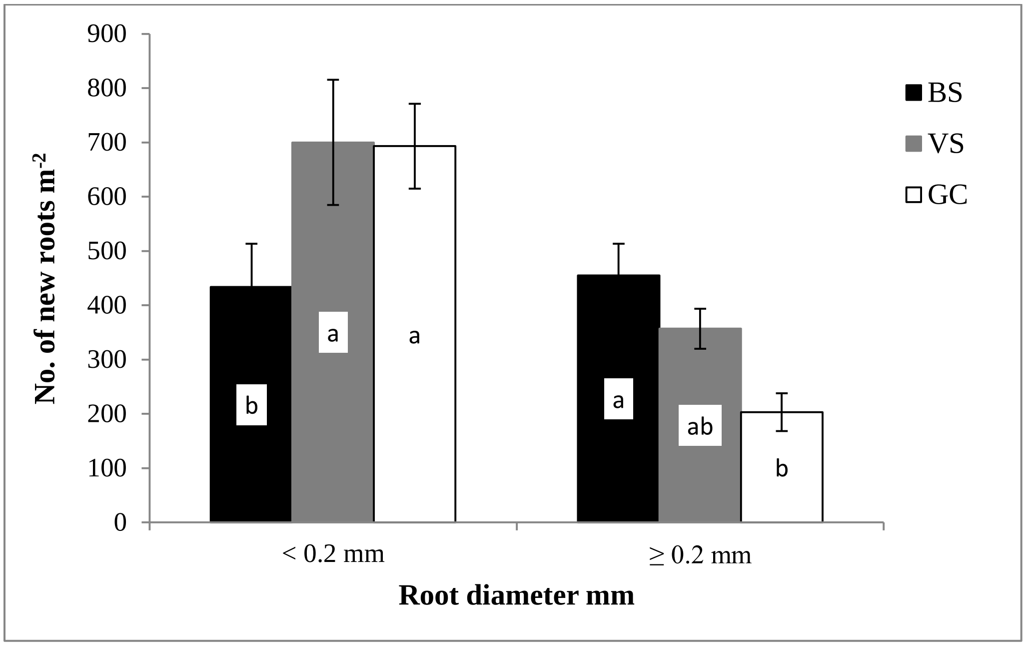

Figure 4. Number of avocado roots m^{-2} < 0.2 mm and ≥ 0.2 mm diameter for treatments BS, VS and GC during the entire study period. Values are the average of 5 replicates (each replicate is 1 tree) for each treatment, ± standard error of the mean. Different letter in each column represent statistical difference among treatments within each root diameter category and were generated from Tukey's honestly significant difference at $P \leq 0.05$.

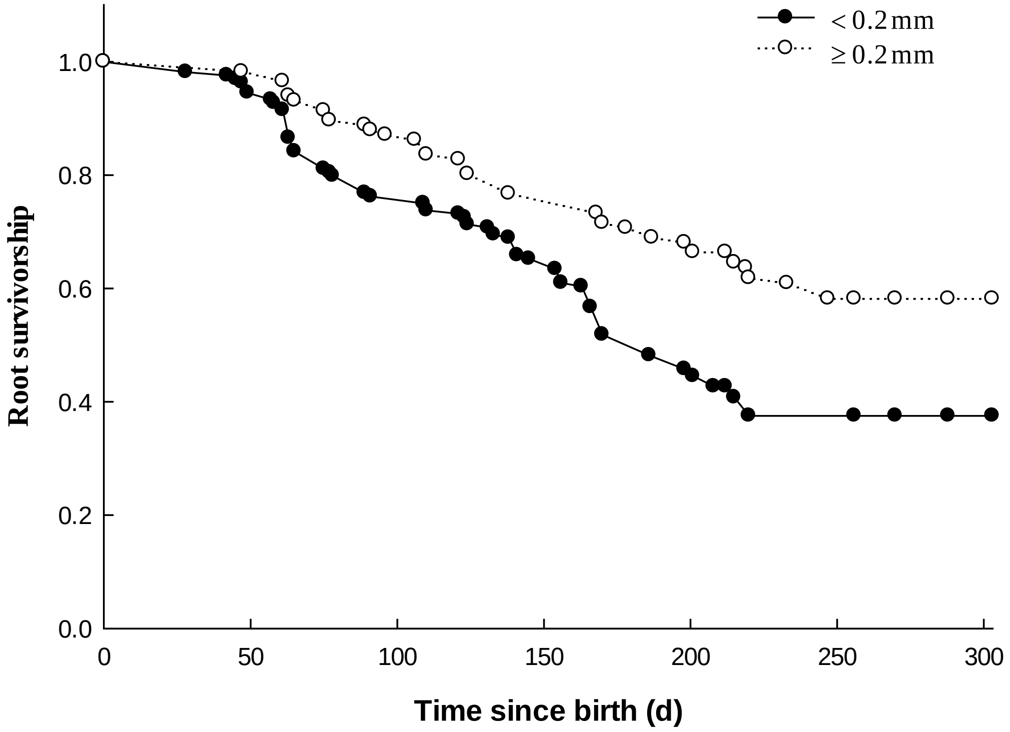

Figure 5. Root survivorship curves from minirhizotron data for avocado roots with diameter <0.2 mm and ≥0.2 mm. Root birth and death are estimated as halfway between successive sampling dates from when a root was not present to the date it first appeared. The first quartile estimate of root life span were 110 and 168 (d) for roots <0.2 mm and ≥0.2 mm, respectively.

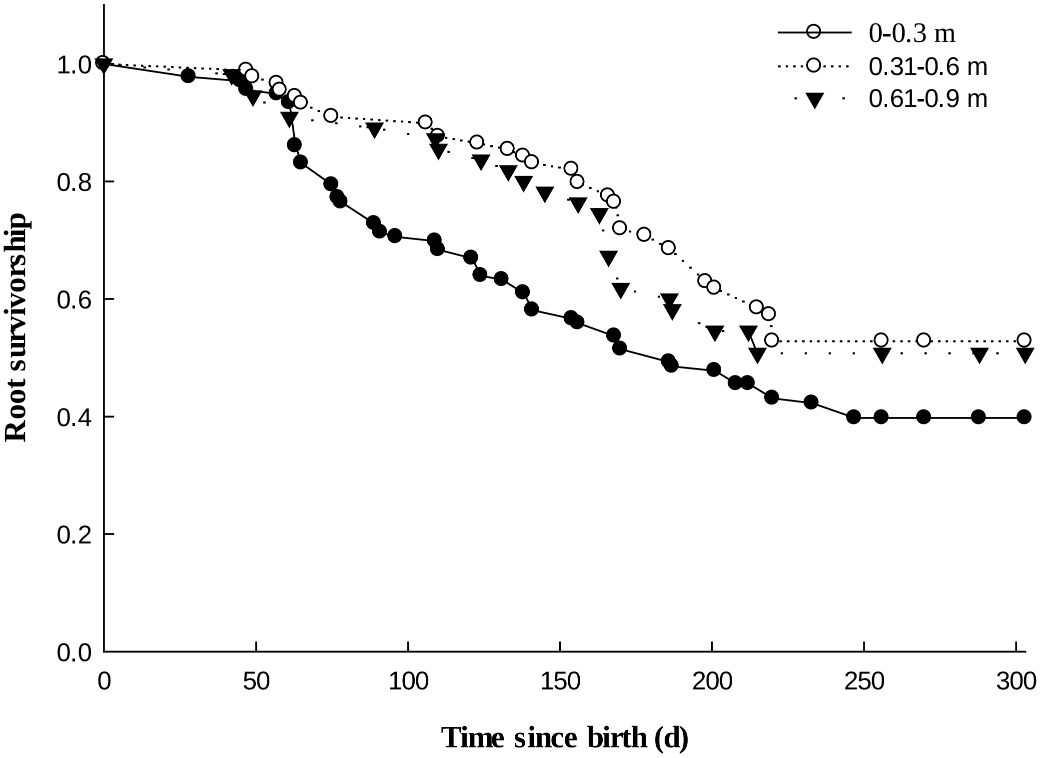

Figure 6. Root survivorship curves from minirhizotron data for avocado roots in three different soil depths: 0-0.3 m; 0.31-0.6 m and 0.61-0.9 m. Root birth and death are estimated as halfway between successive sampling dates from when a root was not present to the date it first appeared. The first quartile estimate of root life span were 89; 170 and 163 (d) for roots in 0-0.3 m; 0.31-0.6 m and 0.61-0.9 m soil depths, respectively.

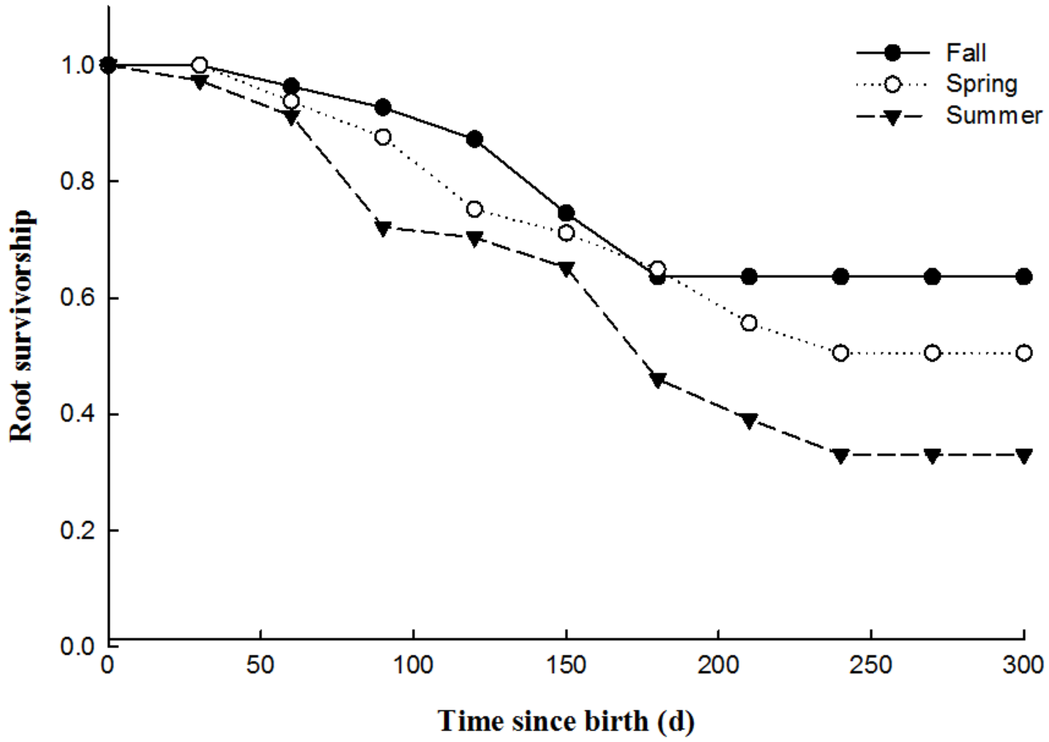

Figure 7. Root survivorship curves from minirhizotron data for avocado roots born in fall, spring and summer of 2009-2010. Root birth and death are estimated as halfway between successive sampling dates from when a root was not present to the date it first appeared. The first quartile estimates of root life span were 145, 138, and 89 (d) for fall, spring and summer, respectively.

Table1. Results of Cox' Proportional Hazards regression analyses for predictor variable of root lifespan, for all roots appearing from Sept. 2009 to June 2010.

Factors	d.f.	Parameter estimate	SE	χ^2 value	*P*-value	level 1	/level 2	Hazard ratio	*P*-value
Season(Ref* = Summer)	2	-	-	11.853	0.003	fall	spring	0.438	0.005
Fall	1	-0.531	0.169	9.886	0.002	fall	summer	0.464	0.002
Spring	1	0.294	0.161	3.354	0.067	spring	summer	1.059	0.812
Treatment (Ref* = GC)	2	-	-	5.082	0.079	VS	BS	1.119	0.609
BS	1	-0.211	0.137	2.364	0.124	BS	GC	0.595	0.033
VS	1	-0.098	0.121	0.659	0.417	VS	GC	0.665	0.063
Soil depth (Ref* = 61-90 cm)	2	-	-	12.641	0.002	31-50	0-30	0.489	0.001
0-30 cm	1	0.407	0.127	10.353	0.001	0-30	61-90	1.648	0.034
31-60 cm	1	-0.315	0.132	5.640	0.018	31-60	61-90	0.801	0.383
Root diameter (Ref* = ≥0.2 mm)	1	-	-	11.853	0.001	≥0.2	<0.2	0.488	0.001
<0.2 mm	1	0.358	0.108	10.956	0.001	-	-	-	-

* The reference season, treatment, soil depth, or root diameter to which lifespans of roots born in other seasons, treatments, soil depths, and root diameters were compared.

Table 2. Results of Cox' Proportional Hazards regression analyses of predictor variable of root lifespan, for roots less than 0.2-mm diameter, appearing from Sept. 2009 to June 2010.

Factors	d.f.	Parameter estimate	SE	χ^2 value	*P*-value	level 1	/level 2	Hazard ratio	*P*-value
Season (Ref* = Summer)	2	-	-	9.284	0.009	fall	spring	0.438	0.005
Fall	1	-0.571	0.202	8.0156	0.004	fall	summer	0.464	0.002
Spring	1	0.388	0.227	2.956	0.086	spring	summer	1.059	0.812
Treatment (Ref* = GC)	2	-	-	8.907	0.011	VS	BS	1.378	0.293
BS	1	-0.420	0.198	4.518	0.034	BS	GC	0.390	0.005
VS	1	-0.099	0.153	0.424	0.515	VS	GC	0.538	0.018
Soil depth (Ref* = 61-90 cm)	2	-	-	12.063	0.002	31-60	0-30	0.413	0.001
0-30 cm	1	0.378	0.154	6.001	0.014	0-30	61-90	1.285	0.370
31-60 cm	1	-0.506	0.161	9.838	0.001	31-60	61-90	0.530	0.035

* The reference season, treatment, soil depth or root diameter to which lifespans of roots born in other seasons, treatments, soil depths and root diameters were compared.