HORTSCIENCE 60(4):519–529. 2025. https://doi.org/10.21273/HORTSCI18329-24

Integrated Approaches Are Needed To Manage Weeds in Organic Apple Orchards

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Keywords. cultivation, herbicide, integrated weed management, *Malus ×domestica*, mulch, sustainable

Abstract. **Prolific weed growth during rainy, humid summers coupled with poor efficacy of available weed management strategies remains a major barrier to adoption of organic apple production in New York. The effects of multiple, in-row weed management strategies on weed cover and biomass, soil health, and tree growth and productivity were assessed via a split-plot experiment implemented in 2016 in a certified organic apple orchard in Ithaca, NY, USA. Main treatments included cultivation with a Wonder Weeder (cultivation), surface-applied wood chip mulch (mulch), and an untreated control (main). Split treatments included ammoniated soap of fatty acids (ammoniated soap), capric/caprylic acid (capric acid), mowing with a string trimmer (mowing), and an untreated control (split). The mulch was applied once, in Spring 2016; all other treatment combinations occurred four times per season, about monthly from May to August. Between 2017 and 2019, nearly all measured soil health parameters increased under the mulch treatment relative to the control (main) treatment. Notably, soil organic matter in the mulch treatment increased from 4.8% in 2016 to 5.2% in 2019 but declined in the cultivation treatment from 4.5% to 4.1% during those years. Regardless of the split treatment, the mulch treatment maintained 16% to 45% less weed biomass than the other main treatments throughout the study. The split treatments became a more significant factor in the latter years. Regardless of the main treatment, the split treatments of ammoniated soap, capric acid, and mowing all maintained less than 200 g·m^{-2} of weed biomass per sampling period, which was significantly less than the control (split) at sample dates 3 and 4 in 2017 and sample dates 2 to 4 in 2018 and 2019. This was mainly due to an abundance of *Symphyotrichum lanceolatum* and *Solidago* spp. in main treatment combinations with the control (split) treatment. Tree growth was greatest in the cultivation treatment, in which trunk cross-sectional area quadrupled between Spring 2016 and Fall 2019. These findings demonstrate that multiple approaches are needed to obtain adequate weed control and balance orchard productivity and soil health during the establishment period of an organic apple orchard in New York.**

Consumer demand for organic fruit is increasing, yet less than 1% of the New York apple (*Malus ×domestica*) orchard area is currently certified as organic (Carlson et al. 2023; US Department of Agriculture, National Agricultural Statistics Service 2022, 2024). Apple growers in New York contend with over 50 direct and indirect arthropod pests and more than 20 plant diseases, which makes producing undamaged and blemish-free fruit very challenging using organic management (Agnello et al. 2017; Peck et al. 2010). The lack of organic production in New York is also related to the high humidity and over 100 cm of annual precipitation, which fosters rampant weed germination and growth. Research from a wide range of locations and climates, including New York, cite weeds as the greatest barrier to increasing organic apple production (Agnello et al. 2017; Granatstein and Mullinix 2008; Granatstein and Sánchez 2009; Hoagland et al. 2008; Peck et al. 2010; Williams et al. 2015).

Weeds can outcompete apple tree roots for nutrients and water, which negatively affects tree growth and fruit yield. From May to July, weeds must be controlled within a 2-m^2 area around each tree to improve leaf nitrogen and prevent yield loss in apple orchards (Breth 2015; Merwin and Ray 1997; Neilsen and Hogue 1985). Weed management is especially critical during the first 5 years after planting, as young trees have a minimal root system and are more susceptible to competition from weeds (Hoagland et al. 2008; Stiles and Reid 1991). Apple orchards are less susceptible to water and nutrient competition once trees reach maturity (Atucha et al. 2011; Stefanelli et al. 2009).

Cultivation, mowing, and mulching are often used in organic apple orchards for weed control, but these practices can come at high financial and horticultural costs compared with conventional herbicides (Bradshaw 2017; Merwin et al. 1995; Mia et al. 2020). For example, a study in New York found that the use of a cultivator or mower had greater labor and equipment costs than managing weeds with synthetic herbicide applications (Peck et al. 2010). Another consideration is the degradation of soil health associated with repeated cultivation over the life of an orchard (Peck et al. 2011). According to the National Organic Program Standard §205.203, organic producers must, "maintain or improve the physical, chemical, and biological condition of the soil and minimize erosion"—all of which can be reduced by repeated cultivation (Mohler et al. 2021). Lastly, management of persistent vine and perennial weeds may necessitate hand weeding, which is time consuming and thus financially prohibitive.

High-density plantings using dwarfing rootstocks are more productive and profitable than more widely spaced systems using semi-dwarfing rootstocks and have become the norm for conventionally managed orchards producing apples for the fresh market in New York (Robinson et al. 1991, 2007). However, dwarfing rootstocks have smaller root systems and are more sensitive to resource competition from weeds that often occur in organic orchard systems. Limited availability of efficacious herbicides that are allowable under the US Department of Agriculture (USDA) National Organic Program (NOP) standards and the risks of tree damage due to mechanical cultivation have contributed to the limited adoption of organic apple production in New York (Agnello et al. 2017; Peck et al. 2010).

In 2016, a split-plot experimental design with three main treatments and four split treatments was implemented in a high-density, certified organic apple orchard in Ithaca, NY. The goal was to test individual and stacked in-row weed management strategies during the establishment period of an organic apple orchard. Treatment effects on the percentage of weed cover and biomass, soil health, foliar nutrient content, and tree growth and productivity were measured. We hypothesized that the mulch treatment would improve soil health parameters such as soil organic matter, respiration, and active carbon. We also hypothesized that "stacked" weed management that combined two treatments would improve weed control relative to treatments used individually. Finally, we hypothesized that treatments that improved soil health and reduced weed biomass would result in greater tree growth and productivity over the course of the study.

Materials and Methods

Study site. The 0.16-ha site was located on Northeast Organic Farming Association of New York (NOFA-NY)–certified organic land at the Cornell Agricultural Experiment Station

Received for publication 20 Nov 2024. Accepted for publication 10 Jan 2025.
Published online 14 Mar 2025.
The project was supported in part by the Arthur Boller Research Fund and grants from the Toward Sustainability Fund. We are appreciative of Cornell University's School of Integrative Plant Science for awarding Kate Brown an Extension Outreach Assistantship. We also thank all the Cornell Orchards Interns and Peck Lab members who spent many hours in the hot summer sun collecting weed, soil, and leaf samples.
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orchards in Ithaca, NY (lat. 42.44519°N, long. 76.45912°W). The soils at the site were 78% Hudson and Collamar silt loams and 22% Hudson silty clay loam, moderately well drained, with 2% to 6% slopes (Soil Science Division Staff 2017). Semidwarf apple trees were previously grown at this site from 1981 to 2006, and the site was fallowed after these trees were removed. In Autumn 2014, the field was plowed, and one line of drainage tile was installed through a wet area at the north end. No cover crop was seeded, and no lime was applied as the soil pH was optimal at 6.8.

The eight tree rows used for this study were located on the easternmost end of a 28-row block planted in Spring 2015. From east to west, the block comprised 15 rows under NOFA-NY–certified organic management, followed by 2 organically managed buffer/transition rows, and 7 conventionally managed rows. The rows were oriented north–south. European black alder (*Alnus glutinosa*) flanked the north and east of the planting, and a 10-m-wide grass buffer strip separated the planting from conventionally managed apples on the south side. A fallow field bordered the west end of the planting for the duration of the study. Further details about the field site and experimental design can be found in the lead author's master's thesis (Brown 2022).

Environmental conditions. Daily minimum, maximum, and mean temperatures in 2016 to 2019 were similar to 30-year (1981 to 2010) historic values, except in 2018, when daily minimum temperatures in May, August, and September were 3.9 to 4.8 °C greater than historic monthly means (https://newa.cornell.edu/; https://www.nrcc.cornell.edu/wxstation/ithaca/ithaca.html). Each year, the average daily temperature increased from budbreak through August and then declined through harvest. Over the 30-year period from 1981 to 2010, average precipitation from May through September was 8.1 to 10.1 cm per month, totaling 46.6 cm. In 2017 and 2019, total precipitation over these months was similar, but rainfall events were less evenly distributed. Precipitation in 2018 was similarly sporadic but totaled 5 cm less than historic monthly means.

Experimental design. Eight rows of 'Honeycrisp (Firestorm)'/'Budagovsky.9' trees were planted in 2015, trained following the tall-spindle system, and spaced 0.9 m between trees and 3.7 m between rows. A randomized, split-plot design with four complete blocks was implemented the following year. The main treatments included cultivation using a Wonder Weeder (Harris Manufacturing, Burbank, WA); mulch (a mix of hard and soft woods sourced from the Cornell University Grounds Department with individual wood chips ranging from 1 to 10 cm in various shapes and surface-applied in a 1.0-m swath centered over the tree row to a 15-cm depth); and an untreated control (main), which had no weed control. The split treatments included ammoniated soap [Final-San-O® (163 L a.i./ha); Certis USA, LLC, Columbia, MD], capric acid [Suppress® Herbicide EC, 6% solution (57 L a.i./ha); Westbridge Agricultural Products, Vista, CA], mowing [using a hand-held string trimmer], and an untreated control (split). The wood chip mulch was applied only once, in May 2016, while all other treatments were repeated four times per season within 1 to 3 d following each aboveground weed biomass sampling. Mechanical cultivation preceded the herbicide application and followed string trimmer mowing. Weeds were controlled within 0.5 m of the center on each side of the tree row. A diverse stand of grass and broadleaf weeds in the aisle was mowed about four times per season. Every fall, a string trimmer was used to cut all weeds in the tree rows down to the soil surface following the onset of tree dormancy.

The split-plot experimental design comprised 4 complete blocks of 12 treatment combinations (3 main × 4 split). Each block consisted of two rows, which were divided into three main plots, one for each main treatment. Main plots were subdivided into four split plots, one for each split treatment. The main plots were separated by six buffer trees, while the split plots were separated by three buffer trees. The percentage of weed cover, aboveground weed biomass, apple leaf tissue samples, soil samples, and soil volumetric water content were collected at the plot level. Flower density, trunk cross-sectional area (TCSA), and fruit yield were collected at the tree level, but mean values per plot were compared among treatments.

Pest and disease management. Pests and disease were managed according to USDA-NOP regulations and local guidelines (Peck and Merwin 2009; Brown 2022). Common orchard pests included oriental fruit moth (*Grapholita molesta*), codling moth (*Cydia pomonella*), plum curculio (*Conotrachelus nenuphar*), apple maggot (*Rhagoletis pomonella*), European apple saw fly (*Hoplocampa testudinea*), San Jose scale (*Quadraspidiotus perniciosus*), potato leafhopper (*Empoasca fabae*), and Japanese beetle (*Popillia japonica*). Diseases included fire blight (*Erwinia amylovora*), apple scab (*Venturia inaequalis*), powdery mildew (*Podosphaera leucotricha*), and the complex of fungal species that causes sooty blotch and flyspeck.

Foliar-applied fertilizer. Nitrogen, magnesium, boron, and zinc fertilizers were foliar-applied to all trees as needed based on annual leaf tissue analyses and according to USDA-NOP guidelines (Brown 2022).

Percent weed cover and weed biomass. The percentage of weed cover and aboveground weed biomass data collection occurred about monthly, between May and August of each year: 18 May, 6 Jun, 7 Jul, and 9 Aug in 2017; 10 May, 31 May, 2 Jul, and 30 Jul in 2018; and 8 May, 4 Jun, 26 Jun, and 29 Jul in 2019. Weed control treatments occurred 1 to 3 d after sampling. At each sampling date, the percentage of cover and aboveground weed biomass samples were collected from within a 0.25-m^2 quadrat placed directly in the tree row at a randomly selected sample location between two trees per plot (n = 48). Each sample location was sampled only once per growing season. The percentage of cover was measured using the Canopeo smartphone application (Patrignani and Ochsner 2015; https://canopeoapp.com/) from the height at which the quadrat was no longer visible on the smartphone screen. All aboveground weed biomass rooted within the

Table 1. Aboveground weed biomass from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA.

	Aboveground weed biomass (g·m^{-2})		
Variables	2017	2018	2019
Main treatments			
Cultivation	134.9 A	177.0 A	225.0 AB
Mulch	82.6 B	112.0 B	191.0 B
Control (main)	151.8 A	163.0 A	260.0 A
Split treatments			
Ammoniated soap	104.1 b	99.0 b	153.0 b
Capric acid	92.5 b	89.1 b	134.0 b
Mowing	110.1 b	112.0 b	127.0 b
Control (split)	185.8 a	302.4 a	490.0 a
Sample date			
1	133.0 YZ	95.7 Y	119.0 X
2	102.0 Y	112.6 Y	192.0 YX
3	112.0 YZ	183.9 Z	247.0 Y
4	146.0 Z	200.3 Z	345.0 Z
Significance			
Main	***	***	**
Split	***	***	***
Sample date	*	***	***
Main × split	NS	NS	NS
Main × sample date	NS	NS	NS
Split × sample date	***	***	***
Main × split × sample date	NS	NS	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey's honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase, beginning of alphabet), split treatments (lowercase), or sample dates (uppercase, end of alphabet). The data represent the mean values for each main treatment, split treatment, or sample date in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 2. Foliar mineral content of leaf tissue samples from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA.

Variables	Calcium ($mg \cdot g^{-1}$)	Carbon ($mg \cdot g^{-1}$)	Copper ($mg \cdot kg^{-1}$)	Potassium ($mg \cdot g^{-1}$)	Magnesium ($mg \cdot g^{-1}$)	Nitrogen ($mg \cdot g^{-1}$)	Phosphorus ($mg \cdot g^{-1}$)	Boron ($mg \cdot kg^{-1}$)	Iron ($mg \cdot kg^{-1}$)	Manganese ($mg \cdot kg^{-1}$)	Zinc ($mg \cdot kg^{-1}$)
2016											
Main treatments											
Cultivation	13.14	472.74 A	8.97 A	10.18 B	2.22	18.09 A	3.02 B	27.18 B	83.54	29.89	39.80
Mulch	12.80	470.30 AB	8.45 AB	11.78 A	2.08	17.34 A	3.66 A	28.76 A	80.76	29.31	42.66
Control (main)	12.40	469.91 C	8.14 C	11.38 A	2.09	16.20 B	3.63 A	28.68 A	83.18	31.49	47.22
Split treatments											
Ammoniated soap	12.71	469.76	8.54	9.76 b	2.21	17.74 ab	3.04 b	27.63	82.15	25.02 b	36.01 b
Capric acid	12.86	471.68	8.53	10.35 b	2.13	18.37 a	2.77 b	27.39	78.97	37.36 a	39.57 ab
Mowing	12.77	471.25	8.51	12.17 a	2.08	16.36 b	3.97 a	28.90	84.42	29.27 ab	48.66 a
Control (split)	12.77	471.25	8.51	12.17 a	2.08	16.36 b	3.97 a	28.90	84.42	29.27 ab	48.66 a
Significance											
Main	NS	*	**	**	NS	**	*	*	NS	NS	NS
Split	NS	NS	NS	***	NS	***	***	NS	NS	*	**
Main × split	NS	NS	*	NS	*	NS	NS	NS	NS	NS	NS
2017											
Main treatments											
Cultivation	13.26 A	458.90 A	27.14	11.58 B	2.84	18.13 A	3.48	35.57	96.07	33.79	143.31 B
Mulch	11.56 B	457.07 AB	24.08	13.01 AB	2.72	16.61 B	3.80	35.53	107.14	44.70	166.15 A
Control (main)	13.62 A	454.93 B	26.03	13.48 A	2.95	16.97 B	4.03	36.79	96.16	44.38	171.55 A
Split treatments											
Ammoniated soap	12.63	455.96	25.30	12.11	2.81 ab	17.50 ab	3.58	37.15	104.05	33.83	156.85
Capric acid	13.28	457.36	24.89	11.92	2.64 b	18.20 a	3.46	35.18	99.61	44.73	151.89
Mowing	12.47	457.57	28.34	13.75	3.17 a	16.88 ab	4.16	37.11	101.15	45.76	174.14
Control (Split)	12.88	456.99	24.47	12.97	2.73 b	16.36 b	3.88	34.41	94.34	39.51	158.46
Significance											
Main	*	**	NS	*	NS	**	NS	NS	NS	NS	**
Split	NS	NS	NS	NS	**	**	NS	NS	NS	NS	NS
Main × split	NS	NS	NS	*	NS	*	NS	NS	NS	NS	NS
2018											
Main treatments											
Cultivation	12.57	457.57	54.99	10.91	2.50	18.44	2.22 Y	34.41	70.33	33.17	271.61
Mulch	11.88	456.19	54.56	12.42	2.42	17.60	3.11 X	34.17	68.26	43.60	269.18
Control (Main)	11.95	455.61	58.51	12.03	2.51	17.09	3.09 X	35.68	69.13	45.10	294.12
Split treatments											
Ammoniated soap	12.46	455.77	56.54	11.61	2.43	17.53 b	2.48 b	33.79	69.84	36.43	274.54
Capric acid	12.27	458.44	55.87	11.35	2.38	18.47 a	2.23 b	33.94	67.86	42.40	263.42
Mowing	11.78	455.72	55.44	11.96	2.50	17.30 b	3.15 a	35.57	70.15	44.41	290.44
Control (split)	12.03	455.90	56.23	12.23	2.60	17.53 b	3.37 a	35.73	69.12	39.24	284.81
Significance											
Main	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS
Split	NS	NS	NS	NS	NS	*	***	NS	NS	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2019											
Main treatments											
Cultivation	6.50 A	469.27	33.06	9.17 B	2.09 A	15.88 A	1.82 B	47.84	59.30 B	40.64	144.27
Mulch	5.64 B	462.58	34.50	10.01 A	1.92 B	14.69 B	2.18 A	48.52	78.74 A	43.72	147.63
Control (main)	6.61 A	452.87	35.90	10.11 A	2.09 A	15.41 AB	2.20 A	46.61	67.62 AB	47.15	152.43

(Continued on next page)

Table 2. (*Continued*)

Variables	Calcium ($mg \cdot g^{-1}$)	Carbon ($mg \cdot g^{-1}$)	Copper ($mg \cdot kg^{-1}$)	Potassium ($mg \cdot g^{-1}$)	Magnesium ($mg \cdot g^{-1}$)	Nitrogen ($mg \cdot g^{-1}$)	Phosphorus ($mg \cdot g^{-1}$)	Boron ($mg \cdot kg^{-1}$)	Iron ($mg \cdot kg^{-1}$)	Manganese ($mg \cdot kg^{-1}$)	Zinc ($mg \cdot kg^{-1}$)
Split treatments											
Ammoniated soap	6.36	456.24	33.57	9.65	2.02 ab	15.42	2.09	47.35	72.71	42.06	141.21
Capric acid	5.99	464.99	34.06	9.35	1.90 b	15.54	1.94	47.78	69.62	48.49	145.39
Mowing	6.33	462.14	34.14	9.80	2.16 a	15.43	2.18	48.39	66.67	45.21	146.83
Control (split)	6.31	462.92	36.19	10.25	2.06 ab	14.93	2.05	47.11	65.21	39.59	159.00
Significance											
Main	***	NS	NS	**	***	**	**	NS	**	NS	NS
Split	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS
Main × split	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey's honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

quadrat was then harvested at the ground level using scissors and/or hand shears. The plants were placed into paper bags and then oven-dried at 70 °C for 7 d before the dry weight was measured. The weed species data are presented in Brown (2022).

Foliar mineral content. Approximately 90 d after full bloom, a representative sample of 50 leaves was collected from each plot. The leaves were collected from roughly the midpoint of the current season's growth and kept in paper bags. Before delivery to the Cornell Nutrient Analysis Laboratory (CNAL, Ithaca, NY, USA), the leaves were rinsed with deionized water to remove residual foliar-applied minerals. Total carbon and total nitrogen were measure by combustion analysis and inductively coupled plasma atomic emission spectroscopy was used to determine micro- and macronutrient content following standard CNAL protocols (https://cnal.cals.cornell.edu/).

Soil physical, chemical, and biological properties. Soil samples were collected approximately 90 d after full bloom. A 2-cm diameter soil core sampler was used to collect soil samples to a 15-cm depth. Soil samples for each plot comprised 12 soil cores (4 locations per plot × 3 soil cores per location). Within each plot, four locations were randomly selected wherein one soil core was collected from directly in the tree row, one was collected from the east side, and one was collected from the west side. Composite samples were kept in plastic, zip-top bags that contained all 12 soil cores from each plot. If same-day delivery to CNAL was not possible, the samples were stored at 2 °C overnight. The samples were tested using the Standard Soil Health Analysis Package (Moebius-Clune et al. 2017; https://soilhealthlab.cals.cornell.edu). This package includes soil pH, organic matter, Modified Morgan extractable P, K, and micronutrients, soil texture, active carbon, wet aggregate stability, soil respiration, total carbon, total nitrogen, predicted autoclave-citrate extractable (ACE) protein test, and predicted available water capacity. The array of tests provides insight into the chemical, physical, and biological characteristics of soil that are most sensitive to short-term variations in management.

Soil volumetric water content. In 2019, soil volumetric water content (VWC) was measured using a Field Scout TDR350 soil moisture meter (Spectrum Technologies, Inc., Aurora, IL, USA) with 7.62-cm soil probes. Soil VWC was measured once per week from 6 Jun to 6 Sep 2019 for a total of 10 measurements. At each sampling date, soil VWC was collected from one location per plot, where weeds had not already been harvested. Because we anticipated that soil VWC directly in the tree row would be greater than on the edges of the tree row in the cultivation treatment, we collected one measurement from the middle, one from the east side, and one from the west side for all 48 plots in the experiment. The average of these three measurements per plot was used for statistical analysis.

Tree growth. TCSA was measured after leaf fall. Calipers were used to take two perpendicular measurements of trunk diameter 40 cm above the graft union of each tree. The two diameter values were averaged and converted to TCSA using the area formula for a circle.

Flower and crop density. Flower clusters per tree were counted at pink stage on approximately 5 May in 2018, 2019, and 2020. The number of flower clusters per tree was divided by TCSA from the previous fall for each sample tree to determine flower density. Harvested fruit number and weight was recorded for each individual tree on 10 Sep 2018 and 10 Sep 2019. Preharvest fruit drops were also counted and included in the total number of fruits per tree, but not the weight of fruit per tree. Crop density was calculated by dividing the total number of fruits (on-tree + drops) by the postharvest TCSA.

Statistical analysis. All data were analyzed in R statistical software, version 1.3.1056 (R Core Team 2014). A linear mixed model was fitted including main treatment [cultivation, mulch, control (main)], split treatment [ammoniated soap, capric acid, mowing, and control (split)], their interactions as fixed effects, and a random block effect. In the case of the percentage of weed cover, the timepoint (sample date) was included as a fixed effect in the model, as was a block × timepoint random effect term. Each year was analyzed separately and subjected to an analysis of variance to determine treatment and interaction effects at the $P \leq 0.05$ level. Tukey's honestly significant difference test was used to identify differences among treatments.

A correlation matrix was created in R using the *ggcorrplot* package (version 0.1.4.1) to visualize the linear relationship among variables (Kassambara and Patil 2023). A principal component analysis (PCA) was conducted including weed biomass, active soil carbon, soil respiration, ACE soil protein index, soil organic matter, wet aggregate stability, available water capacity, total soil carbon and nitrogen, foliar nitrogen, and TCSA. The PCA was performed separately for each year from 2017 to 2019, with the weed biomass data normalized via log transformation for 2017 and 2019.

Results

Aboveground weed biomass. Aboveground weed biomass was significantly affected by main treatment, and there was also an interaction between split treatment and sample date in each year (Table 1). Despite yearly increases in aboveground weed biomass for all treatments in this study, the mulch treatment consistently had 50 to 70 $g \cdot m^{-2}$ less weed biomass than the control (main), while weed biomass in the cultivation treatment was always similar to the control (main), regardless of the split treatment.

Regardless of the main treatment, ammoniated soap, capric acid, and mowing all significantly reduced weed biomass compared with the control (split) during most sample dates (Table 1). Weed biomass in control (split) combinations were greater than for other split treatments by sample

Table 3. Macro- and micronutrient content of soil samples (15-cm depth) collected from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA.

Variables	Carbon ($mg \cdot g^{-1}$)	Potassium ($mg \cdot kg^{-1}$)	Magnesium ($mg \cdot kg^{-1}$)	Nitrogen ($mg \cdot g^{-1}$)	Phosphorus ($mg \cdot kg^{-1}$)	Iron ($mg \cdot kg^{-1}$)	Manganese ($mg \cdot kg^{-1}$)	Zinc ($mg \cdot kg^{-1}$)
2017								
Main treatments								
Cultivation	29.48 A	114.83 B	336.32	2.53	8.30 B	4.63 B	15.71 B	1.26
Mulch	31.76 A	133.53 A	326.20	2.51	9.67 A	10.54 A	23.31 A	1.36
Control (main)	27.2 B	106.34 B	310.24	2.39	7.69 B	5.69 B	13.94 B	1.40
Split treatments								
Ammoniated soap	28.66	123.89	349.66 a	2.45	8.78	6.82	17.32	1.10 b
Capric acid	29.99	114.25	296.64 b	2.53	8.70	6.94	18.82	1.42 ab
Mowing	29.07	110.85	340.31 ab	2.41	7.60	6.92	17.11	1.23 ab
Control (split)	30.21	123.95	310.41 ab	2.54	9.14	7.14	17.37	1.62 a
Significance								
Main	***	***	NS	NS	***	***	***	NS
Split	NS	NS	**	NS	NS	NS	NS	*
Main × split	NS	NS	NS	*	NS	NS	NS	NS
2018								
Main treatments								
Cultivation	27.25 B	191.45 B	369.04	1.73	5.66 B	1.52	4.67	1.13 B
Mulch	32.10 A	239.68 A	374.43	1.86	7.00 A	3.48	8.11	1.43 AB
Control (main)	28.17 B	182.12 B	348.94	1.73	5.15 B	2.48	5.17	1.50 A
Split treatments								
Ammoniated soap	28.54	214.64	386.93	1.68	5.83	1.81	4.98	1.11
Capric acid	29.45	213.31	340.12	1.81	6.48	3.15	7.43	1.42
Mowing	28.66	194.94	383.92	1.77	5.48	2.35	5.56	1.43
Control (split)	30.03	194.78	345.58	1.84	5.95	2.66	5.97	1.46
Significance								
Main	***	***	NS	NS	***	NS	NS	*
Split	NS	NS	NS	NS	NS	NS	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS	NS
2019								
Main treatments								
Cultivation	27.22 B	113.14 B	309.89	2.78	6.36 B	3.27	16.73 B	2.27 B
Mulch	36.65 A	134.52 A	310.03	2.58	8.66 A	4.57	24.31 A	3.26 A
Control (main)	28.01 B	103.97 B	282.52	2.41	6.15 B	4.36	17.12 B	3.04 AB
Split treatments								
Ammoniated soap	29.27	121.36	316.27	2.42	6.51	3.39	17.67	2.85
Capric acid	31.20	119.04	280.46	2.66	7.02	4.05	19.61	2.93
Mowing	30.69	117.86	319.51	2.61	6.92	4.03	19.70	2.71
Control (split)	31.34	110.58	287.01	2.68	7.78	4.79	20.56	2.93
Significance								
Main	***	***	NS	NS	***	NS	***	**
Split	NS	NS	*	NS	NS	NS	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey's honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

date 3 in 2017 and by sample date 2 in 2018 and 2019. By sample date 4 in 2019, the average weed biomass in the control (split) treatments were nearly 950 $g \cdot m^{-2}$, while other split treatments yielded an average of 120 $g \cdot m^{-2}$. Rapid growth of *Solidago* spp. and *Symphyotrichum lanceolatum* were the main contributors to differences in weed biomass among the split treatments (Brown 2022).

Foliar nutrient content. Regardless of the split treatment, foliar C and N were significantly greater for the cultivation treatment than for control (main) in 2016 and 2017 (Table 2). N was also greater in the cultivation treatment compared with the mulch treatment in 2019. The split treatment had no effect on foliar C in any year, but foliar N in the capric acid split treatment was significantly greater than the control (split) in the first 3 years. Notwithstanding the statistical differences among treatments, foliar N was deficient for all treatment combinations in all years according to the minimum threshold of 22.0 $mg \cdot g^{-1}$ for young bearing apple trees (Stiles and Reid 1991).

Treatment effects on foliar P and K were similar in all years (Table 2). The cultivation treatment had 0.4 to 0.9 $mg \cdot g^{-1}$ less foliar P and 1 to 2 $mg \cdot g^{-1}$ less K than the other main treatments, and this difference was significant in 3 of the 4 sample years. Among the split treatments, ammoniated soap and capric acid had less foliar P and K than the control (split) and mowing treatments, but this was only significant for both elements in 2016 and for P in 2018. Although trends were similar for both foliar P and K, foliar K was deficient in nearly all treatments, regardless of year, while foliar P was always adequate. Foliar Ca was often deficient, especially in the mulch treatment which had 1 to 2 $mg \cdot g^{-1}$ less foliar Ca than the other main treatments in 2017 and 2019. Foliar Ca content was unaffected by the split treatments. Foliar Mg was deficient (less than 3.5 $mg \cdot g^{-1}$) in all treatment combinations regardless of year. Mn was deficient in 71% to 94% of experimental units each year. Other foliar micronutrients had satisfactory leaf content, and statistical differences among main or split treatments were rare and never occurred for more than 1 year.

Soil mineral content. Between 2017 and 2019, total soil C increased under the mulch treatment from 31.8 to 36.7 $mg \cdot g^{-1}$ (Table 3). For the cultivation treatment and the control (main), soil C was relatively unchanged, averaging 28 $mg \cdot g^{-1}$, over the 3 years. As a result, soil C was significantly greater for the mulch treatment than the other main treatments in 2018 and 2019. Total soil N did not vary by main or split treatment at any time during the study.

Table 4. Soil biophysiochemical properties determined from soil samples (15-cm depth) collected from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA.

Variables	Available water capacity ($g \cdot g^{-1}$)	Wet aggregate stability (%)	Soil organic matter (%)	Autoclave-citrate extractable soil protein index ($mg \cdot g^{-1}$)	Soil respiration ($mg \cdot g^{-1} CO_2$)	Active carbon ($mg \cdot g^{-1}$)	Soil pH
2017							
Main treatments							
Cultivation	0.35 AB	26.65	4.46 AB	9.99	1.04 B	0.72 B	6.63
Mulch	0.37 A	22.79	4.81 A	11.67	1.22 A	0.81 A	6.76
Control (main)	0.33 B	23.49	4.18 B	9.86	0.99 B	0.68 B	6.53
Split treatments							
Ammoniated soap	0.35	19.72 b	4.51	10.53	1.03 b	0.76	6.76
Capric acid	0.35	22.78 b	4.47	10.08	1.00 b	0.73	6.52
Mowing	0.35	23.66 b	4.31	9.79	1.06 b	0.70	6.69
Control (split)	0.35	31.07 a	4.64	11.62	1.25 a	0.75	6.59
Significance							
Main	**	NS	***	*	**	***	NS
Split	NS	***	NS	NS	**	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS
2018							
Main treatments							
Cultivation	0.33 B	15.78 B	4.78 B	10.45 B	0.91 B	0.77 B	6.85
Mulch	0.36 A	21.60 A	5.33 A	13.03 A	1.12 A	0.92 A	6.99
Control (main)	0.33 B	19.41 AB	4.66 B	10.78 B	1.06 AB	0.82 B	6.79
Split treatments							
Ammoniated soap	0.34	17.01	4.87	11.24	0.88 b	0.84	7.02
Capric acid	0.35	18.15	4.98	11.96	1.04 ab	0.85	6.79
Mowing	0.33	20.24	4.87	10.88	1.02 ab	0.81	6.89
Control (split)	0.33	20.33	4.97	11.59	1.18 a	0.84	6.81
Significance							
Main	***	**	***	**	**	***	NS
Split	NS	NS	NS	NS	**	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS
2019							
Main treatments							
Cultivation	0.33 B	29.57 B	4.06 B	10.35 B	0.97 C	0.90 B	6.74
Mulch	0.35 A	36.38 A	5.21 A	16.24 A	1.46 A	1.07 A	6.72
Control (main)	0.34 B	32.29 B	4.09 B	11.25 B	1.13 B	0.88 B	6.59
Split treatments							
Ammoniated soap	0.33	29.25 b	4.26	11.79	1.07 b	0.94	6.83
Capric acid	0.34	32.67 ab	4.51	12.82	1.04 b	0.94	6.62
Mowing	0.34	33.28 ab	4.49	12.53	1.20 b	0.94	6.70
Control (split)	0.34	35.80 a	4.56	13.34	1.42 a	0.96	6.58
Significance							
Main	**	***	***	***	***	***	NS
Split	NS	*	NS	NS	***	NS	NS
Main × split	NS	NS	NS	NS	NS	NS	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey's honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

The mulch treatment resulted in significantly greater soil P, K, and Mn content compared with cultivation and control (main), regardless of year (Table 3). From 2017 to 2019, the mulch treatment increased soil P by 21% to 38%, soil K by 21% to 28%, and soil Mn by 44% to 57% compared with the other main treatments. Soil Mg content was unaffected by main treatment and averaged 329 $mg \cdot kg^{-1}$ among the main treatments over the course of the study. Soil Fe was similar among treatments, except in 2017 when soil Fe for the mulch treatment was 10.5 $mg \cdot kg^{-1}$, double the soil Fe content for the other main treatments. Soil Zn was inconsistently affected by main treatment. In 2018, soil Zn for the cultivation treatment was 33% lower than the control (main). In 2017 and 2019, however, soil Zn was not significantly different from the control (main) for either main treatment. The split treatments had minimal effects on soil mineral content.

Soil health. The mulch treatment generally had the greatest values for all aspects of soil health measured in this study (Table 4). Soil organic matter under the mulch treatment increased from 4.8% to 5.2% between 2017 and 2019, while soil organic matter for the cultivation treatment declined from 4.5% to 4.1% over this same period. Wet aggregate stability for the mulch and cultivation treatments remained similar to the control (main) treatment through 2018, but the mulch treatment had significantly greater aggregate stability than the cultivation and control (main) treatment in 2019. The mulch and cultivation treatments were further differentiated from each other by soil respiration rates in 2019 (1.5 and 1 $mg \cdot g^{-1}$ CO_2, respectively). Soil respiration for the mulch treatment was 29% greater than for the control (main), while for the cultivation treatment, it was 14% lower than the control (main). Similar to soil mineral content, differences in soil health among the main treatments were observed regardless of the split treatments except for 2019 when wet aggregate stability in the ammoniated soap treatment was 18% lower than control (split).

Soil volumetric water content. The main treatments significantly influenced soil VWC during six of the ten sampling dates in 2019 (Table 5). On 6, 13, and 25 Jun, soil VWC in the mulch treatment was 6% to 11% greater than the control (main) and cultivation treatments. Soil VWC was similar among the main treatments between 8 Jul and 8 Aug. On 19 and 26 Aug and 6 Sep, soil VWC in the mulch treatment was similar to the main control (main), while the cultivation treatment reduced soil

Table 5. Soil volumetric water content measured on 10 sampling dates in 2019 from within the tree row of a split-plot experiment comparing weed control tactics in a certified organic orchard of ‘Honeycrisp’/‘Budagovsky.9’ apple trees grown in Ithaca, NY, USA.

	Volumetric water content ($m^3 \cdot m^{-3}$)									
Treatment	6 Jun	13 Jun	25 Jun	8 Jul	16 Jul	23 Jul	8 Aug	19 Aug	26 Aug	6 Sep
Main treatments										
Cultivation	43.4 B	33.5 B	38.0 B	28.5	20.8	28.5	27.0	26.2 B	23.3 B	27.9 B
Mulch	48.7 A	36.9 A	42.5 A	29.8	19.9	30.8	24.4	32.0 A	27.7 A	33.8 A
Control (main)	44.3 B	34.7 AB	39.2 B	29.3	18.6	30.8	25.5	33.0 A	28.6 A	33.8 A
Split treatments										
Ammoniated soap	45.9	35.0	41.0	31.6 a	22.3 a	32.0 a	27.2 ab	31.6 a	26.8 a	33.0 a
Capric acid	44.8	36.4	40.2	31.7 a	22.8 a	30.9 a	29.5 a	32.2 a	29.2 a	33.3 a
Mowing	46.1	35.8	40.6	30.3 a	20.2 a	31.7 a	24.7 bc	32.0 a	28.6 a	33.6 a
Control (split)	45.0	33.0	37.7	23.2 b	14.0 b	25.4 b	21.1 c	25.8 b	21.6 b	27.5 b
Significance										
Main	***	*	***	NS	NS	NS	NS	***	***	***
Split	NS	NS	NS	***	***	***	***	***	***	***
Main × split	NS	NS	NS	NS	NS	NS	NS	*	NS	NS

Means in the same column followed by the same letter are not significantly different within sample date according to Tukey’s honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment on a given day.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

VWC 17% to 21% compared with the control (main).

From 8 Jul through 6 Sep, split treatment was a significant factor in soil VWC (Table 5). During this period, soil VWC was similar among the mowing, capric acid, or ammoniated soap treatments, but 21% to 55% greater than the control (split), regardless of main treatment.

Tree growth. In Spring 2016, before initial treatment application, the TCSA was uniform among all treatments with mean value of 1.2 cm^2 (Table 6). Between Spring 2016 and Winter 2019, the TCSAs of trees in the cultivation treatment increased 42% more than those in the control (main) and 48% more than those in the mulch treatment. Within the cultivation treatment, final TCSAs in Winter 2019 were similar across all split treatments with an average of 4.8 cm^2. The TCSAs for the mulch treatment were unaffected by split treatment in any year and in 2019, the average TCSA was 3.8 cm^2. By contrast, within the control (main), TCSAs increased 279% in the ammoniated soap and capric acid split treatments, while TCSAs in the mowing and control (split) increased 221% over the course of the study. Ultimately, trees in the control (main) × ammoniated soap or capric acid treatments had an average TCSA of 4.5 cm^2, which was statistically similar to the final TCSAs for the cultivation treatment. Additionally, the TCSAs for the control (main) × ammoniated soap and control (main) × capric acid treatments were 0.8 cm^2 greater than the TCSAs for control (main) × mowing and control (main) × control (split) treatments.

Flower and crop density. In 2018, flower density was similar among the main treatments, regardless of split treatment, and the average density was 2.6 clusters/cm^2 TCSA (Table 7). Split treatment alone did not affect flower density, but there was a two-way interaction between the main and split treatments in 2018. Within the mulch treatment, mulch × ammoniated soap had 4.7 clusters/cm^2 TCSA, which was significantly more than the 0.5 clusters/cm^2 TCSA for mulch × control (split). Flower density did not differ among the split treatments in the cultivation treatment or the control (main) in 2018. In 2019, flower density was only significantly impacted by main treatments; the cultivation treatment had 0.4 clusters/cm^2 TCSA compared with 0.04 clusters/cm^2 TCSA for the mulch treatment. Neither treatment resulted in a flower density significantly different from the control (main).

Similar to flower density, there was a two-way interaction between the main and split treatments affecting crop density in 2018 (Table 7). The mulch × ammoniated soap treatment yielded 1.6 fruits/cm^2 TCSA, which was four times greater than mulch × control (split) treatment. Crop density was significantly less for the main control (main) × capric acid treatment compared with Control (Main) × Control (Split) treatment, 0.6 vs. 1.7 fruits/cm^2 TCSA, respectively. Crop density was statistically similar among all split treatments in the cultivation treatment with an average of 1 fruit/cm^2 TCSA. In 2019, the main treatment was the only significant factor for crop density. Within the cultivation treatment, crop density was 0.3 fruit/cm^2 TCSA, which was ten times greater than the mulch treatment (0.03 fruits/cm^2). Neither cultivation nor mulch resulted in crop density significantly different from the control (main).

Correlation matrix. A correlation matrix was created to evaluate the relationships among the dependent variables (Fig. 1). Over the course of the study, soil health parameters were often positively correlated with one another, but these relationships were not always statistically significant. In 2019, there was a significant positive correlation among all soil health parameters except for total soil nitrogen. Alternatively, TCSA was always significantly negatively correlated with soil health parameters apart from total soil N in 2019 and wet aggregate stability in 2017. TCSA and leaf N were always positively correlated to each other, and this

Table 6. Trunk cross-sectional area from a split-plot experiment comparing weed control tactics in a certified organic orchard of ‘Honeycrisp’/‘Budagovsky.9’ apple trees grown in Ithaca, NY, USA.

	Trunk cross-sectional area (cm^2)				
Treatment	Spring 2016	Winter 2016	Winter 2017	Winter 2018	Winter 2019
Main treatments					
Cultivation	1.18	1.64	2.58 A	3.98 A	4.79 A
Mulch	1.21	1.56	2.21 B	3.12 B	3.78 B
Control (main)	1.22	1.54	2.27 B	3.19 B	3.85 B
Split treatments					
Ammoniated soap	1.21	1.63 ab	2.47 ab	3.62 a	4.36 a
Capric acid	1.22	1.70 a	2.55 a	3.87 a	4.64 a
Mowing	1.18	1.44 c	2.10 c	3.06 b	3.73 b
Control (split)	1.20	1.51 bc	2.22 bc	3.01 b	3.64 b
Significance					
Main	NS	NS	***	***	***
Split	NS	***	***	***	***
Main × split	NS	NS	NS	**	**

Means in the same column followed by the same letter are not significantly different within each sample date according to Tukey’s honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 7. Flower density and crop density from a split-plot experiment comparing weed control tactics in a certified organic orchard of ‘Honeycrisp’/‘Budagovsky.9’ apple trees grown in Ithaca, NY, USA.

	Flower density (clusters/cm^2 TCSA)		Crop density (fruit/cm^2 TCSA)	
Treatment	2018	2019	2018	2019
Main treatments				
Cultivation	2.77	0.37 A	0.94	0.24 A
Mulch	2.72	0.04 B	0.96	0.03 B
Control (Main)	2.34	0.21 AB	1.02	0.13 AB
Split treatments				
Ammoniated soap	3.02	0.16	1.15	0.1
Capric acid	2.83	0.34	0.91	0.22
Mowing	2.00	0.14	0.81	0.13
Control (Split)	2.44	0.17	0.97	0.06
Significance				
Main	NS	***	NS	***
Split	NS	NS	NS	NS
Main × split	**	NS	***	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey’s honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase). The data represent the mean values for each main or split treatment in a given year.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

relationship was significant in 2017 and 2019. Lastly, weed biomass was significantly negatively correlated with soil water capacity in 2017 and soil volumetric water content in 2019.

Principal component analysis. Species scores indicated which variables were most strongly related to each principal component, with a species score near ±1 being most significantly related to each principal component (Fig. 2; Table 8). There was a significant separation between the mulch treatment and the other main treatments along principal component 1 (PC1) in every year. Regardless of year, PC1 was most strongly correlated with soil health parameters including total soil C and total soil N (2017 and 2018); organic matter, ACE protein index, and respiration (2017 and 2019); and active C and wet aggregate stability (2018 and 2019). There was no significant separation among the split treatments along PC1, except in 2019 when the ammoniated soap split treatment was significantly different from the control (split). PC1 explained at least 42% of the variation in every year.

There were no main × split treatment interaction effects for PC1 or PC2; however, there was significant separation among the main treatments and, separately, among the split treatments for principal component 2 (PC2) in every year (Fig. 2; Table 8). In 2017, PC2 was most strongly correlated with TCSA and leaf N. There was significant separation between the cultivation and mulch treatments in that year, as well as between the control (split) and mowing treatment. In 2018, PC2 was most strongly correlated with leaf N. Among the main treatments, there was significant separation between the cultivation treatment and the control (main), while among the split treatments, there was a significant separation between the capric acid and mowing treatments in 2018. Lastly, in 2019, PC2 was most strongly correlated with volumetric water content and the log-transformed weed biomass at sample date 4. Among the main treatments, there was a significant separation between the mulch treatment and the control (main), while the control (split) was significantly different from the other split treatments.

Discussion

Maintaining adequate weed control and improving soil health can oftentimes be competing goals in organic agriculture. While the mulch treatment reduced weed biomass and improved soil health relative to the untreated control (main), it did not achieve sufficient tree growth and productivity. In fact, no combination of organic weed management tactics resulted in a commercially acceptable yield for a young orchard. Reig et al. (2019) demonstrated the annual yield of ‘Honeycrisp’/‘B.9’ in the first 10 years after planting to be approximately 11.8 kg/tree in a tall spindle production system in New York. In our study, only 59% of trees bore fruit in 2018 and only 21% bore fruit in 2019, the fourth and fifth years after planting, respectively. Of those trees that did bear fruit, the average yield was 1.1 kg/tree in 2018 and 0.6 kg/tree in 2019, well under the yields needed for economic sustainability during the establishment years for an apple orchard.

Although weed competition was reduced by the mulch treatment, the weeds were not eliminated. Additionally, the mulch treatment caused greater spring soil moisture retention that possibly led to poor root growth and inadequate nitrogen uptake. Soil VWC was 6% to 10% greater in the mulch treatment than the control (main) in June, a critical period for nutrient uptake due to the overlapping high growth rates of shoots, roots, and fruit (Psarras et al. 2000). Apple trees rely on internal N reserves rather than soil N for initial spring growth, but then there is a period of rapid N uptake from bloom through the end of shoot growth each year (Cheng and Fuchigami 2002; Cheng and Raba 2009; TerAvest et al. 2010). If N uptake is limited during this period, tree growth would be inhibited. Increased soil moisture can have other drawbacks in heavier soils such as poor root growth and soil N loss via denitrification or leaching (Hoagland et al. 2008; Merwin et al. 1992). The consequences of high soil moisture would be exacerbated in wet years, and increased soil VWC where wood chips or other organic mulches were

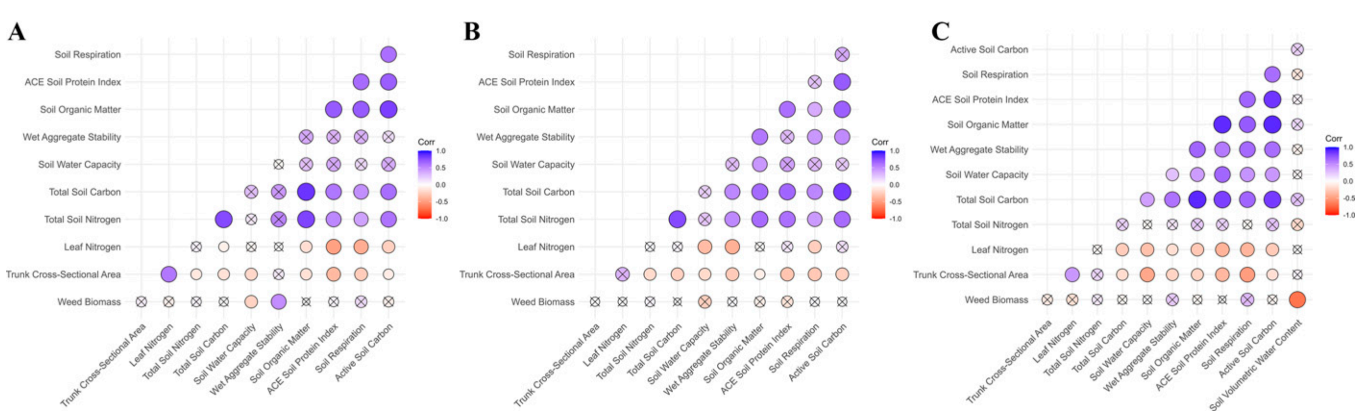

Fig. 1. Correlation matrices for visualization of linear relationships among all variables measured during the 3 study years [2017 (**A**), 2018 (**B**), and 2019 (**C**)] from a split-plot experiment comparing weed control tactics in a certified organic orchard of ‘Honeycrisp’/‘Budagovsky.9’ apple trees grown in Ithaca, NY, USA. Weed biomass represents biomass collected at sample date 4; the data were log-transformed in 2017 and 2019 to normalize data. × = not significant at $P \leq 0.05$; ACE = autoclave-citrate extractable.

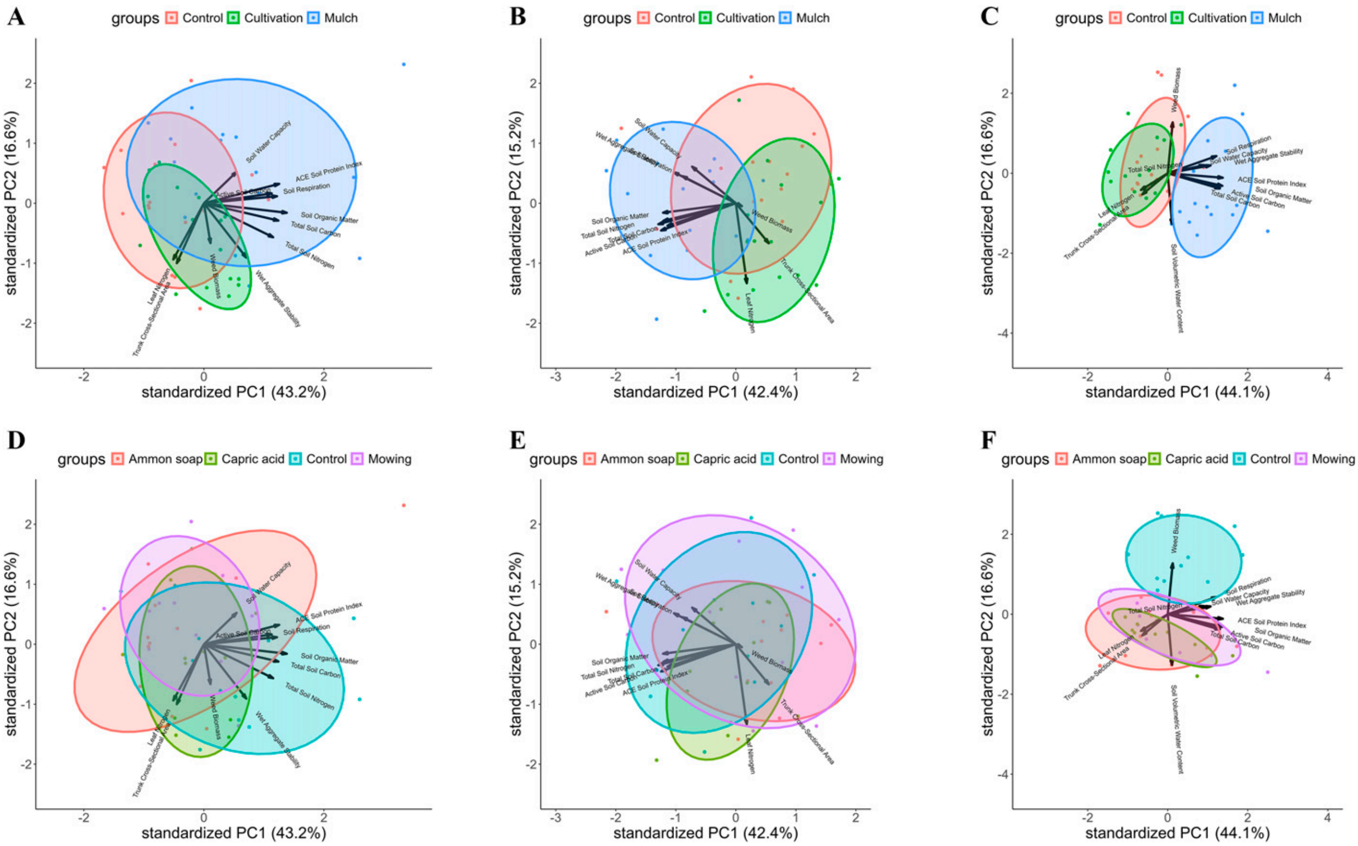

Fig. 2. Biplots of principal component analysis for variables measured from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA. Ellipses represent main treatments in 2017 (**A**), 2018 (**B**), and 2019 (**C**) and split treatments in 2017 (**D**), 2018 (**E**), and 2019 (**F**). PC1 = principal component 1; PC2 = principal component 2.

applied has been reported in other studies across a range of soil types (Granatstein and Mullinix 2008; Hoagland et al. 2008; Merwin et al. 1992; Walsh et al. 1996).

If there was less precipitation and/or if the study had been conducted in lighter textured soils, then perhaps results would have been different. For example, a study in Long Island, NY, found that mulches can be an effective practice to sustain apple tree growth and yields in soils that have adequate water drainage (Aller et al. 2022). While wood chip mulch is a viable weed control option for some organic orchards, in heavier textured soils with poor water drainage, like those at the experimental site, wood chip mulch may not be a suitable weed management tactic during the establishment period.

The cultivation treatment had the greatest increase in TCSA; however, by the fourth year of the experiment, the cultivation treatment resulted in significantly lower soil microbial respiration compared with the control (main) treatment and maintained a weed biomass similar to the control (main) treatment throughout the experiment. Minimal weed biomass reduction in the cultivation treatment relative to the control (main) treatment was perhaps due to the cultivation events being too shallow or infrequent to suppress the

Table 8. Mean separation of position of main and split treatments along principal components 1 and 2 visualized in Fig. 2. Principal component analysis included weed biomass, trunk cross-sectional area, leaf nitrogen, soil nitrogen, soil carbon, and soil health parameters from a split-plot experiment comparing weed control tactics in a certified organic orchard of 'Honeycrisp'/'Budagovsky.9' apple trees grown in Ithaca, NY, USA.

	2017		2018		2019	
Treatment	Principal component 1	Principal component 2	Principal component 1	Principal component 2	Principal component 1	Principal component 2
Main treatments						
Cultivation	0.081 B	−0.392 A	0.443 B	−0.317 A	0.534 B	−0.059 AB
Mulch	−0.439 A	0.358 B	−0.622 A	0.031 AB	−0.802 A	0.254 B
Control (main)	0.358 B	0.034 AB	0.179 B	0.286 B	0.268 B	−0.196 A
Split treatments						
Ammoniated soap	0.100	0.153 ab	0.211	−0.081 ab	0.265 b	0.327 b
Capric acid	0.093	−0.203 ab	0.052	−0.321 a	0.057 ab	0.426 b
Mowing	0.165	0.331 b	−0.065	0.264 b	−0.032 ab	0.233 b
Control (split)	−0.358	−0.281 a	−0.197	0.138 ab	−0.290 a	−0.987 a
Significance						
Main	**	**	***	**	***	**
Split	NS	*	NS	**	*	***
Main × split	NS	NS	NS	NS	NS	NS

Means in the same column followed by the same letter are not significantly different within each year according to Tukey's honestly significant difference test ($P \leq 0.05$). Letters designate significant differences among main treatments (uppercase) or split treatments (lowercase).

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

growth of the abundant, rhizomatous weeds present at the study site. In other words, soon after the cultivation event occurred, these weeds quicky re-established. More frequent cultivation may diminish weed growth by exhausting underground storage reserves (Mohler et al. 2021). However, the associated time, labor, and equipment costs, as well as potential negative consequences for soil health, particularly through soil organic matter loss, need to be considered (Merwin et al. 1994, 1995; Peck et al. 2011). Soil organic matter in the cultivation treatment was not different from the control (main) treatment in our study, but it declined annually and would likely continue to do so from repeated cultivation events.

Although the mulch treatment did not increase TCSA, weed biomass was reduced compared with the control (main) treatment, and soil health metrics were improved compared with both control (main) and cultivation treatments. Similar orchard soil health improvements following wood chip mulch application have been reported in many studies (Choi et al. 2011; Glover et al. 2000; Haynes 1980; Peck et al. 2011; St. Laurent et al. 2008; Yao et al. 2005). In our experiment, the mulch treatment increased soil P and K compared with both the control (main) and cultivation treatments. Other studies at the same research farm observed similar effects of organic mulches on soil P and K (Merwin and Stiles 1994; Peck et al. 2011). Soil Mn content also increased in the mulch treatment compared with control (main) and cultivation treatments but was not reported in the other above-mentioned studies from this site. Perhaps longer-term studies would find that mulches can build soil quality to allow for greater productivity in the latter years of the orchard.

Correlation matrices indicated that leaf N was the only factor positively correlated with TCSA, and soil health metrics were often negatively correlated with TCSA. Variability in foliar N was likely the result of differences in soil N availability or uptake, as foliar nitrogen fertilizer applications were uniform across the experimental trees. It is possible that the C-rich wood chip mulch may have resulted in microbial immobilization of otherwise plant-available N as Hoagland et al. (2008) documented using isotopic analyses. Soil organic matter decomposition related to cultivation events may have improved soil availability of nitrogen for plant growth and thus may be a reason why the cultivation treatment had the largest trees in this experiment.

The ammoniated soap, capric acid, and mowing split treatments all reduced weed biomass compared with the control (split) across all main treatments and sample dates. However, soil health metrics were not different among these split treatments. Clearly, a stacked weed control approach can have positive benefits for weed suppression in organic apple orchards, but further work is needed to develop treatment combinations, rates, and application timings that work across a range of pedoclimatic conditions and weed species.

Our results also highlight the critical importance of choosing an appropriate scion/rootstock combination for the site and management system. The combination of ‘Honeycrisp’/‘B.9’ is known to be a particularly low vigor tree. This scion/rootstock combination was intentionally chosen for the experiment because the trees would be very susceptible to weed competition and thus responsiveness to the imposed treatments. For commercial organic apple orchards under the limitations of allowed fertility amendments, a more vigorous scion/rootstock combination would be advisable.

Conclusions

Based on the results from this and other studies, the success of in-row weed management strategies depends on soil texture, the scion/rootstock vigor, the ability to maintain adequate tree fertility, and the existing weed community. Additionally, organic orchard managers need to minimize weed competition during the establishment years when adequate tree growth is essential for developing sufficient canopies for fruit bearing. This is especially important in organic orchards, where there is a greater cost of production and readily plant-available sources of N are limited. All the weed management strategies tested in this experiment required specialized equipment, whether an herbicide applicator, a side-mounted cultivation or mowing tool, or a mulch spreader. However, once the equipment is purchased, only herbicide applications would have an annual cost for materials. The cost of wood chip mulch varies greatly depending on whether it is locally available, but it only needs to be applied every 3 to 5 years. Overall, weed management strategies must be tailored to the site and age of the orchard with an emphasis on providing a suitable soil environment for root growth and nutrient uptake. While mulching and stacked weed management strategies to achieve these goals will have a greater implementation cost, they will likely pay a return on investment over the long-term through lower weed competition and thus greater fruit yields.

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