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Under-vine Management Impacts Soil Properties and Leachate Composition in a New York State Vineyard

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Abstract. **Four under-vine management treatments were established in 2011 in a *Vitis vinifera* L. 'Cabernet Franc' vineyard in the Finger Lakes region of New York: cultivation (CULT), native vegetation (NV), white clover *Trifolium repens* L. (WC), and glyphosate herbicide (GLY) as the control. Previously installed drainage lysimeters were used to monitor nutrient and pesticide concentrations in leachate water samples. Differences in the physical structure of soils among treatments were only observed in the 4th year of the study when the top 6 cm of CULT soils had greater bulk density than the other treatments, and less porosity and available water capacity than WC soils. WC soils had 17% greater organic matter than CULT soils, and 46% greater aggregate stability than GLY soils. Soil microbial respiration was generally greater in NV and WC treatments than GLY and CULT. Dissolved organic carbon (DOC) leachate concentrations were greater in GLY and CULT compared with NV and WC, having annual mean DOC leachate concentrations as much as 36% greater than the cover crop samples. Mean annual total nitrogen (TN) leachate concentrations of CULT and NV were less than GLY and WC samples by as much as 86%. In 2012, GLY soils leached greater concentrations of imidacloprid insecticide and more imidacloprid metabolites than the other three treatments, with the proportion of samples testing positive for measurable concentrations of imidacloprid or imidacloprid metabolites at least five times greater in GLY than the other treatments. Cumulatively, these factors demonstrate the potential of under-vine cover crops to maintain soil quality and decrease the leaching of nutrients and agrochemicals in vineyards in comparison with conventional practices.**

There is interest in the use of under-vine cover crops in viticultural regions with ample precipitation to compete with vines for water and nutrients to help limit excessive vigor (Centinari et al., 2016; Hatch et al., 2011). In addition to the potential benefits of reduced vine vigor, cover crops are being investigated for their potential to protect and improve soils that are normally kept weed free with herbicides or cultivation (Novara et al., 2011). This could be particularly advantageous in regions like the Finger Lakes of New York where vineyards are predominantly located on slopes in close proximity to lakes, and pollution from runoff and leaching of nutrients and agrochemicals is of increased concern.

Weed control in the under-vine row can be important for the production of high-quality grapes. Tall or climbing weeds can block sunlight from reaching leaves in the canopy, reduce carbohydrate production, or interfere with harvest (Wolf, 2008). Competition from weeds for light, water, and nutrients can be particularly severe in newly planted vineyards while young vines are establishing canopies and root systems (Bordelon and Weller, 1997). Herbicide application in the under-vine row is common due to its high degree of efficacy and relative low cost of weed control; cultivation is another popular chemical-free method of weed control but it is more labor intensive due to the frequency with which it must be performed (Wolf, 2008).

Although herbicide applications and cultivation are effective at controlling weed populations, they can also negatively impact soil quality. A lack of soil cover increases the severity of erosion and runoff, raising concerns with these weed control strategies to conserve vineyard soil and prevent pollution of local watersheds (Battany and Grismer, 2000). Exposure of bare soil also results in greater impact from raindrops, which weakens and breaks aggregates apart, increasing the erosivity of soils, and contributing to the formation of surface crusts (Epstein and Grant, 1973). Weed management strategies that do not leave soil bare therefore offer the potential to prevent erosion and runoff. Cultivation stimulates the loss of soil organic matter by disturbing the soil profile and exposing organic materials where they can be metabolized by microorganisms (Six et al., 1998), and the application of glyphosate herbicide is capable of lowering populations of some soil microbes (Schnürer et al., 2006).

Cover crops offer a means of groundcover management that suppresses weed populations by outcompeting them for resources like space or light, and maintains cover over the vineyard floor, reducing the negative impacts of exposing bare soil (Teasdale, 1998). Unlike cultivation and herbicide application, cover crops add organic residues to the soil and have the potential to stimulate more microbial activities (Sparling, 1997; Steenwerth and Belina, 2008). Collectively, soil organic matter provides many benefits to the physical, chemical, and biological properties of soils, making management practices that conserve it crucial for the long-term sustainability of vineyard soils.

By increasing organic matter concentrations and altering the leaching in soils, cover crops may also impact the movement of pesticides such as imidacloprid in the vineyard. Imidacloprid leaching is lower in soils with greater organic matter due to the sorption of imidacloprid to organic matter, providing a potential means of reducing leaching (Cox et al., 1998). Additionally, there are no known studies that have investigated the influence of cover crops on imidacloprid leaching, but some studies have found groundcover to impact the rate and concentration of pesticide leaching in soils (Merwin et al., 1996).

Imidacloprid is a systemic neonicotinoid insecticide, and the second most widely applied agrochemical in the world (Goulson, 2013). Its popularity is largely due to its effectiveness against a wide range of insect pests and the long-term protection from pests it provides (Jeschke et al., 2010). In the eastern United States, it is used to control potato leafhopper (*Empoasca fabae* Harris), japanese beetles (*Popillia japonica* Newman), and grape berry moth (*Paralobesia viteana* Clemens) in vineyards (Van Timmeren et al., 2012). The distribution of imidacloprid throughout the plant can provide lasting protection to all plant tissue, from both root- and foliage-feeding pests. A single application of imidacloprid to grapevines can provide effective control of glassy-winged sharp shooters for over 3 months (Byrne and Toscano, 2006). However, imidacloprid can be lethal to nontarget insects and aquatic invertebrates, and reduce the

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foraging ability of pollinators, raising concerns regarding its movement and persistence (Alexander et al., 2007; Stoughton et al., 2008; Yang et al., 2008).

The objective of this study was to determine if cover crops planted in the under-vine row of a vineyard could improve the physical, chemical, and biological properties of soil in comparison with conventional weed management practices.

Materials and Methods

Vineyard site and experimental design. The study was conducted from 2011 to 2014 in an ≈0.25-ha research vineyard located ≈350 m from the eastern shore of Cayuga Lake, in Lansing, NY, in the Finger Lakes American Viticultural Area (42°34′15″N, 76°35′39″W, 124 m elevation). The vineyard soils are classified as a Hudson–Cayuga silt loam (Soil Survey Staff, 2013), on a 5% to 8% westward facing slope. The vines, *V. vinifera* 'Cabernet Franc' cl. 1 grafted on 3309C rootstock, were planted in 2008 with 2.8-m row spacing. Vine rows were planted perpendicular to the slope of the hill with an orientation of 31° north-northwest.

The vines were planted 1.8-m apart, cane-pruned, and trained on a two-tier flat bow vertical shoot-positioned trellis. The vineyard was equipped with a pressure compensating drip irrigation system (UniRam; Trickl-eez Company, Biglerville, PA) with emitters spaced 61 cm apart with a discharge rate of 2.3 L/h. This system was run twice during the experiment: for 6 h on 29 June and again on 2 July 2012 due to perceived vine water stress. Disease pressure was controlled by standard spraying practices for *V. vinifera* (Wolf, 2008).

Four under-vine groundcover treatments were established in 1-m-wide strips under vines in 2011. The vineyard consisted of 17 rows, with each row consisting of six panels, with four vines per panel. The interior four panels of the eight even-numbered rows were designated as treatment panels. Each under-vine groundcover treatment was randomly established in one of the four treatment panels of the even-numbered rows. Odd-numbered rows and end panels of treatment rows were maintained with glyphosate herbicide when needed as guard (buffer) panels.

Alleyways were planted with either fine-leaf fescue (*Festuca duriuscula* L.) or tall fescue (*Fesctuca arundinacea* Schreb.) in Spring 2010, and maintained by periodic mowing. The study was arranged in a split-plot design with four replicates. Alley sod type was the main plot, and under-vine treatment was the split-plot.

Treatment panels in rows bordered by tall fescue alleys contained a drainage lysimeter placed between vines. These lysimeters were installed a year before the groundcover treatments were established and used to collect leachate water for analysis of nutrient and agrochemical content. In the northeastern United States, a few scion buds on each vine are often protected from cold temperatures by hilling soil over the graft union (Wolf, 2008); however, due to the buried drainage lysimeters in this study, hilling was not an option. In the winters of 2010–11 and 2011–12, rye (*Secale cereale* L.) straw was placed in a strip in the center of the under-vine row and removed in the spring. However, rye produces benzoxazinones that are allelopathic to both monocots and dicots and prevent seed germination (Barnes and Putnam, 1986), and we subsequently noted suppressed vegetative growth where rye straw was spread. To avoid further impact of the straw on vegetation growth, bags filled with gravel in the winter of 2012–13, and bags filled with sawdust in the winter of 2013–14 were placed around graft unions to protect scion buds.

The four under-vine treatments included GLY, CULT, NV, and WC maintained in a 1-m-wide strip under the vines. Representing conventional vineyard practices, glyphosate herbicide was applied twice per year in the GLY treatment, once in late May or early June and again in late July or early August. Makaze glyphosate (Loveland Products, Greeley, CO), N-(phosphonomethyl)glycine in the form of its isopropylamine salt, was diluted to a 2% solution, and applied at a rate of 2.9 kg a.i./ha with a backpack sprayer. In the CULT treatment, cultivation was performed over the entire treatment area with a grape hoe by hand to a depth of ≈10 cm when average vegetation height reached ≈30 cm. Vegetation disturbed by cultivation was left in place on the soil surface. In the WC treatment, white clover (*T. repens* 'Dutch White') was seeded at 10 kg·ha^{-1} in mid to late April each year and mowed when average vegetation height reached ≈30 cm. The NV treatment consisted of allowing naturally occurring vegetation to grow, which was mowed using a push mower when average height reached ≈30 cm. Herbicide application, cultivation, and mowing dates can be found in Table 1. A list of species found in NV can be found in the work of Karl (2015).

Data collected on the impact of under-vine groundcover treatments on the grapevine growth, yield and the sensory qualities of wines can be found in the work of Karl (2015) and Karl et al. (2016).

Weather data. Weather data for the site were recorded from the Cornell University Network for Environment and Weather Applications Lansing Station (newa.cornell.edu), located ≈150 m north of the vineyard at a similar elevation. In 2011, the precipitation gauge was not functioning from 6 May through 18 May, 28 May through 3 June, and 30 July through 31 Oct. During these dates, precipitation data from a weather station being used by our research program in another viticultural study located 9.2 km north of the research site was used. In 2013, the precipitation gauge was not functioning from 1 Aug. through 12 Sept. On these dates, precipitation data from a Lansing, NY Weather Underground weather station, located ≈6.3 km southeast of the site was used. Precipitation and temperature data from 1 Apr. through 31 Oct. were used to estimate rainfall and growing degree days for the growing season (with a base threshold of 10 °C) for each growing season.

Plant cover and biomass. At berry set and veraison in 2013 and 2014, a square framed area of 0.06 m^2 divided into 100 identical subunits using a string grid was used to estimate percent plant coverage of soil in the under-vine treatments. Each subunit was evaluated for the presence of living plant tissue to calculate the percent coverage. Living plant tissue occupying more than 50% of a subunit was recorded as having plant cover. Three framed areas were randomly selected within each treatment block during each measurement period. Aboveground biomass was collected within two of these squares during veraison. Samples were dried for 48 h at 60 °C and weighed (Sartorius ELT103, accuracy ±0.001, Goettingen, Germany). In 2013, clover in the biomass samples was separated from other plant tissue and weighed separately in the WC treatment.

Soil sampling procedure. Soil samples were collected on 5 Sept. 2011, 9 Aug. 2012, 10 Aug. 2013, and 7 Aug. 2014. Bulk composite soil samples were used to analyze soil organic matter, nutrients, pH, wet aggregate stability, and soil respiration. These samples were collected by mixing three random samples of ≈1 L from the top 15 cm of soil within each experimental unit. These samples were then spread out on a countertop and dried overnight before being submitted for analysis or prepared for measurement of soil respiration.

An intact soil core was taken from each experimental unit on soil sampling dates as well. Two stainless steel rings each measuring 60 mm tall × 73 mm in diameter were taped together and driven into the soil using a wooden block and hammer. An empty ring was placed on top of the upper ring when its top was almost full and used to push the stacked rings slightly below the surface. The stacked rings were then dug out, excess soil cut away with a trowel, and the ends protected with plastic caps. These cores were used to measure porosity, penetration resistance, and bulk density.

Soil organic matter, nutrients, and pH. Dried soil samples were submitted to the

Table 1. Date of groundcover treatments: glyphosate herbicide application in the glyphosate treatment (GLY), hand cultivation in the cultivation treatment (CULT), and mowing in native vegetation (NV) and white clover (WC) treatments.

Treatment	2011	2012	2013	2014
GLY	May, July	May, July	27 May, 2 Aug.	6 June, 1 Aug.
CULT	May	June	16 May, 4 July, 7 Sept.	19 May, 29 July
NV	June, August	June, August	17 June, 7 Sept.	19 May, 10 Sept.
WC	—	—	17 Sept.	13 June, 10 Sept.

Cornell Nutrient Analysis Laboratory (Ithaca, NY) for measurement of soil organic matter, nutrients, and pH. Soil organic matter was calculated by loss on ignition after being heated for 2 h at 550 °C. Macro- and micronutrients were measured using inductively coupled argon plasma spectrophotometry after extraction in Morgan's solution (1:5 soil: solution ratio). P was measured by colorimetric methods (Soil Survey Staff, 2014), and pH was measured in a 1:1 dilution (v/v) of soil and water (Soil Survey Staff, 2014).

Aggregate stability. Aggregate stability of bulk soil samples was measured in 2013 and 2014. Dried bulk soil samples were passed through a 2-mm sieve, then placed on a 0.25-mm sieve, and the aggregates that did not pass through were retained. These aggregates, between 0.25 and 2 mm, were spread on a 200-mm-diameter 0.25-mm sieve and placed 50 cm below a rainfall simulator. Over the course of 5 min, the rainfall simulator delivered 12.5 mm water in droplets on each sample (Gugino et al., 2009). The soil remaining on the sieve and the lost material that fell through during the simulated rain were individually collected, dried, and weighed. The proportion of the soil retained on the sieve was calculated to determine aggregate stability.

Soil respiration. Each bulk soil sample was passed through a 2-mm sieve, placed in metal cylinders with nylon mesh bottoms on a sand tension table under vacuum pressure, and removed when water tension equilibrated to Ψ = –10 kPa. Fifty grams of soil was placed in a 250-mL airtight jar along with 20 mL of 0.5 M NaOH in a plastic vial (Fisher Scientific, Pittsburg, PA) and kept in the dark at 30 °C. Over the course of 6 weeks, weekly measurements of the electrical conductivity of the NaOH samples were compared with two blank samples (50 g of autoclaved sand) and a fully CO_2 saturated standard (0.25 M Na_2CO_3) to calculate weekly respiration of CO_2 (Rodella and Saboya, 1999). Soil was dried at 105 °C and then weighed after the experiment to determine dry weight.

Porosity, penetration resistance, and bulk density. Top and bottom soil cores were separated from one another, and the bottoms of both cores were covered with nylon gauze attached with rubber bands. These samples were placed in water reaching to the top rim of the cores to fully saturate the soil over the course of 24 h. Cores were equilibrated to three water tensions to estimate the volume and distribution of pore diameters for the top (0–6 cm) and bottom (6–12 cm) soil depths of the under-vine treatments (Moebius-Clune et al., 2008). Macroporosity (pore diameters > 1000 µm) was calculated gravimetrically by measuring the loss in water mass after saturated cores drained freely for 3 h (Ψ = –0.3 kPa). Mesoporosity (pore diameters 1000–10 µm) was calculated from the loss in water mass after cores previously equilibrated to Ψ = –0.3 kPa were then placed on a sand tension table under vacuum pressure and equilibrated to Ψ = –10 kPa. To determine total porosity and bulk density, cores were then oven-dried at 105 °C. Microporosity (pore diameters 10–0.2 µm) was determined using subsamples of resaturated oven-dried soil equilibrated to Ψ = –1500 kPa on a ceramic high-pressure apparatus. Available water capacity was calculated from the loss of water from –10 to –1500 kPa.

Penetration resistance was measured on the top surfaces of each core immediately after they were equilibrated to –10 kPa using a 30° angle, 4-mm-diameter cone micropenetrometer pushed into the soil to a depth of 50 mm at a rate of 8 mm·s^{-1} (Moebius-Clune et al., 2008).

Soil water infiltration. Infiltration rates of water into the soil of under-vine treatments were measured using Cornell Sprinkle Infiltrometers (Ogden et al., 1997) on 1 Sept. 2011, 5 Oct. 2012, 10 Oct. 2013, and 28 Aug. 2014. The infiltrometers consisted of a portable rainfall simulator positioned on top of a 235-mm i.d. metal ring inserted 7 cm into the soil, with an overflow hole flush with the down-slope soil surface. The rainfall simulator then dripped water onto the soil surface until a consistent rate of runoff was achieved. The infiltration rate was calculated by subtracting the rate of runoff exiting the ring from the rate of water entering from the rainfall simulator (Oliveira and Merwin, 2001).

Lysimeter placement and design. Sixteen subsoil drainage lysimeter troughs were installed in the vineyard in the summer of 2010, one in each experimental unit in rows bordered by tall fescue sod alleys. The lysimeters were Tuff Stuff (Terra Bella, CA) plastic catchment basins measuring 107 cm long 61 cm wide, and 33 cm deep with a 152-L volume, buried in the middle of the under-vine row between two treatment vines, with the top rim of the basin level with the vineyard floor. A 1.9-cm diameter flexible drainage pipe was attached to a drainage hole drilled in the lower bottom rim of the lysimeter that drained under the between row alley and ended at a collection station buried in the adjacent downhill vine row. The drainage hole was covered with a piece of plastic mesh and gravel. The collection station consisted of a 90° plastic elbow that was fitted to a screw cap with an overflow mechanism attached to a 250-mL high-density polyethylene collection bottle (Fisher Scientific, Pittsburg, PA).

Leachate collection and filtration. Beginning in 2011 and continuing until the end of 2014, leachate samples were collected after precipitation events and stored in a –15 °C freezer. The number of samples collected and analyzed following a precipitation event was dependent on the volume of leachate in individual sample bottles. Samples were kept, and analyzed when ≈100 mL or more of leachate was collected. For analysis, samples were first filtered into a vacuum flask through a glass fiber filter with a 0.45-µm pore diameter (G6 Glass Fiber Filter Circle; Fisher Scientific, Waltham, MA).

DOC and TN leachate chemical analyses. Filtered samples were analyzed for DOC and TN concentrations. Analyses were performed using a TOC-V (CPH) with an attached Total Nitrogen 1 unit (Shimadzu Scientific Instruments, Columbia, MD) at Pennsylvania State University in State College, PA. DOC was measured using high-temperature catalytic oxidation, using the methodology described by Sugimura and Suzuki (1988). TN was measured using chemiluminescence detection after high-temperature catalytic combustion at 720 °C, using the methodology described by Clesceri et al. (1998).

The DOC and TN concentrations of leachate samples were compared for differences among treatments for each calendar year of the study. In 2011, 77, 77, 68, and 69 leachate samples from GLY, CULT, NV, and WC treatments were analyzed, respectively; and in 2012, 81, 89, 64, and 70 leachate samples from GLY, CULT, NV, and WC treatments were analyzed, respectively. In 2013, 82, 73, 67, and 64 leachate samples from GLY, CULT, NV, and WC treatments were analyzed, respectively. In 2014, 40, 34, 35, and 28 leachate samples from GLY, CULT, NV, and WC treatments were analyzed, respectively.

Imidacloprid application and leachate analysis. On 16 July 2012, imidacloprid insecticide was sprayed on the vines at a rate of 112 g a.i./ha in the form of Provado® 1.6 flowable insecticide (Bayer Crop Science, Triangle Park, NC). Over a period of 2 to 43 d after the application, and on 10 different dates, 66 leachate samples (15 from GLY, 18 from CULT, 17 from NV, and 16 from WC) were collected (Karl, 2015). Imidacloprid was applied on 6 Aug. 2013 in the same manner and rate as in 2012. Forty samples were collected over a period of 3 to 47 d after the application on four dates (10 samples from each treatment). These were filtered and sent to the USDA National Science Laboratories in Gastonia, NC, for analysis of imidacloprid and its metabolites: imidacloprid des nitro HCl, imidacloprid olefin, imidacloprid olefin des nitro, and imidacloprid urea. Samples were measured with the Association of Analytical Community's Official Method 2007.01, which uses an acetonitrile and water solution to analyze samples with liquid chromatography and tandem mass spectrometry detection (Lehotay 2007).

Statistical analysis. Soil, plant cover, and leachate data were analyzed using JMP Pro version 10.0.2 (SAS Institute, Cary, NC). Soil respiration, organic matter, pH, nutrient analysis, infiltration, aggregation, penetration, bulk density, and porosity data were measured using a single sample from each treatment panel. These measurements, as well as plant cover and biomass data, were analyzed for differences using a mixed model analysis of variance (ANOVA), with treatment and alley sod type as fixed variables, and split-plot replicate and row as random variables. In 2011, only data from tall fescue bordered treatment panels were collected for soil respiration, infiltration, penetration, bulk density, and porosity measurements; sod type was not used as a fixed variable in this analysis. A logit transformation of all percentage data was performed before analysis.

Leachate samples were analyzed for differences in DOC and TN concentrations among treatments by comparing samples collected during the calendar year using a mixed model ANOVA. Years were independently analyzed, with treatment as a fixed variable and collection date and row as random variables. DOC and TN data were transformed with a natural log to achieve a normal distribution of data. Tukey's honestly significant difference test at a 5% significance level was used to compare means among treatments. Reported *P* values in Tables 3–7 are for the main treatment effect of groundcover.

Leachate samples tested for concentrations of imidacloprid and its metabolites in 2012 were analyzed for differences among treatments using a nominal logistic fit model. An odds ratio test at a 5% significance level was used to compare means among treatments. Treatments were compared by the proportion of samples testing positive for imidacloprid in trace (<1 pbb) or measurable (>1 pbb) concentrations. Treatments were also compared by the proportion of samples with measurable imidacloprid concentrations (>1 pbb), and the proportion of samples testing positive for imidacloprid metabolites (trace or measurable concentrations).

Results

Alleyway sod type did not have a statistically significant impact on any measurements taken during this study, with the exception of microbial respiration in 2012. Samples from rows bordered by fine leaf fescue alleys had a mean weekly respiration of 1.82 mg CO_2/g soil, 29% more than the average tall fescue weekly respiration rate of 1.41 mg CO_2/g soil ($P = 0.024$). Anecdotally, there was no visual difference in sod type. Because no other impacts of alley sod type were measured in the study, data presented in this study only address the impact of under-vine treatment.

Weather data. The 2012 growing season was the warmest of the study (Table 2). The 2011 and 2013 growing seasons had similar heat accumulations to one another, whereas the 2014 growing season was the coolest of the study. The 2011 and 2014 growing seasons were comparatively dry and had similar accumulations of precipitation, whereas the 2013 growing season was the wettest of the study.

Plant cover and biomass. The GLY control treatment effectively suppressed vegetation growth in the under-vine row throughout the 2013 and 2014 growing seasons (Table 3). Samples were not collected to quantify vegetative growth in the treatments in the earlier years of the study, but we observed that the GLY treatments were essentially clear of vegetation through most of the previous growing seasons. Percent cover was under 10% for both measurement dates in 2013 and under 1% for both dates in 2014. Vegetative dry weight was also under 1 g·m^{-2} for all dates in 2013 and 2014.

The cover crops NV and WC established nearly complete groundcover of the under-vine area, with over 95% cover in Sept. 2013 and both quantification dates in 2014. In June 2013, however, cover was lower in both treatments. Vegetative dry weight ranged between 15.8 and 46.5 g·m^{-2} for the cover crops. In 2013, the WC cover crop did not establish well, and clover only made up 23% of vegetative dry weight (Table 3). In 2014, the WC cover crop established more successfully, with ≈52% of the vegetative biomass clover on both sampling dates. The poor establishment may have resulted from white clover seed being dispersed into plots with preexisting resident vegetation that inhibited the growth of newly germinated seeds.

The CULT treatment maintained a moderate suppression of vegetative growth, between the low level of plant growth achieved in the GLY control and the high degree of cover in the NV and WC treatments. Percent cover and dry weight for the CULT treatment ranged between 21% and 58% cover and 2.5 and 10.1 g·m^{-2} across treatment dates. Because cultivation was performed when average weed height reached 30 cm, and the entire under-vine area was thoroughly cultivated, biomass and cover fluctuated markedly between these two points in time.

Soil respiration. Soil from treatments planted with under-vine cover crops had the greatest soil respiration rates during laboratory analysis over the course of the study (Table 4). NV soil respiration was as much as 43% greater than GLY and 45% greater than CULT. WC soil respiration was as much as 36% more than GLY and 39% more than CULT. In 2013 and 2014, NV soil respiration was 31% and 28% greater than WC microbial respiration, respectively. There were no differences between WC and either CULT or GLY in 2013 and 2014.

Soil organic matter, nutrients, and pH. There were few differences in soil nutrient concentrations (data not shown; see Karl, 2015). In 2011 and 2014, WC soil had lower P concentration at 1.9 and 2.0 ppm than GLY, which contained 3.2 and 3.7 ppm. In 2012, CULT soils had 169 ppm of K compared with 270 ppm in WC. In 2013, NV soils contained 104 ppm K, while GLY contained 142 ppm and CULT contained 136 ppm. In 2014, NV soils had 0.6 ppm of Zn while GLY contained 0.4 ppm. Despite these statistically significant differences, all soil nutrient concentrations were within adequate ranges except for P, which was found to be deficient according to soil nutrient recommendations for vineyards (Wolf, 2008), and these differences were not consistent among years. By 2014, WC soils contained the highest organic matter at 3.4% while CULT soils had the lowest at 2.8%.

Soil water infiltration. There were no differences in saturated soil infiltration rates among treatments during all four years of the study (data not shown; see Karl, 2015).

Aggregate stability. In 2013, there was no difference in soil aggregate stability among treatments. In 2014, WC soils had 36% greater aggregate stability than GLY and 23% greater than CULT, with WC soil maintaining 74.8% of aggregate mass after the simulated rain event (data not shown).

Porosity, penetration resistance, and bulk density. There was no impact of treatment on soil core variables from 2011 to 2013 (Table 5). In 2014, bulk density of the CULT upper depth was 13% greater than in the WC upper depth. Total porosity was 16% less, and available water capacity was 12% less in the CULT upper depth soil than in WC. Total porosity was 11% less in the CULT upper depth than in NV in 2014. There were no differences found on soil core variables at lower depths (data not shown; see Karl, 2015).

Leachate DOC and TN. Average DOC concentrations were greater in GLY and CULT leachate samples than NV and WC samples over the calendar years of 2011–13 (Table 6). In 2014, GLY and CULT DOC concentrations were greater than in WC, and CULT DOC concentrations were greater than NV. Yearly average GLY DOC leachate concentrations were as much as 32% and 39% greater than NV and WC DOC concentrations, respectively. Yearly average CULT DOC leachate concentrations were as much as 33% and 36% greater than NV and WC DOC concentrations, respectively.

There was a pattern of DOC leachate concentrations increasing during the spring in April and May, and a period of the highest leaching of the year during autumn in September and October for all treatments, but with greater DOC leaching from CULT and GLY than from NV and WC plots (Fig. 1). Spikes in DOC leaching in the cover crops NV and WC appeared to follow mowing events.

Total nitrogen leachate concentrations varied among treatments and years (Table 6), and were generally higher in the GLY and WC treatments, and lower in the CULT and NV treatments. In 2011, NV samples had 59% lower, and CULT leachate samples had 38% lower TN concentration than GLY. In

Table 2. Accumulation of growing degree days (GDD) base 10 °C, and precipitation from April through October in 2011–14.

	GDD base 10 °C				Precipitation (mm)			
Month	2011	2012	2013	2014	2011	2012	2013	2014
April	46	36	37	32	46	76	67	78
May	201	244	209	183	41	59	52	63
June	301	308	282	297	57	49	113	149
July	412	423	411	346	19	79	115	108
August	315	365	333	316	89	93	104	64
September	251	225	197	224	172	105	135	23
October	77	98	117	101	79	136	68	9
Total	1,604	1,699	1,585	1,498	503	597	654	496

Table 3. Vegetative cover, vegetative dry weight, and proportion of clover in vegetation mass in under-vine groundcover treatments in 2013 and 2014.

	% Surface area cover	Dry wt ($g \cdot m^{-2}$)	% Dry wt clover	% Surface area cover	Dry wt ($g \cdot m^{-2}$)	% Dry wt clover
Treatment	27 June 2013			23 June 2014		
GLY	5 ± 2 b	—	—	1 ± 0 c	0.3 ± 0.1 d	0.0 ± 0.0 c
CULT	54 ± 5 a	—	—	49 ± 4 b	6.3 ± 0.9 c	0.0 ± 0.0 c
NV	69 ± 4 a	—	—	99 ± 1 a	24.8 ± 1.3 a	24.5 ± 4.3 b
WC	56 ± 7 a	—	—	96 ± 1 a	15.8 ± 1.8 b	51.6 ± 5.6 a
P value	<0.001	—	—	<0.001	<0.001	<0.001
	7 Sept. 2013			27 Aug. 2014		
GLY	8 ± 2 c	0.6 ± 0.1 c	—	0 ± 0 c	0.2 ± 0.0 b	0.0 ± 0.0 c
CULT	58 ± 7 b	10.1 ± 1.4 b	—	21 ± 3 b	2.5 ± 0.5 b	0.0 ± 0.0 c
NV	98 ± 1 a	31.7 ± 2.4 a	—	100 ± 0 a	46.4 ± 5.1 a	17.1 ± 4.0 b
WC	98 ± 1 a	31.7 ± 3.1 a	23.3	100 ± 0 a	38.7 ± 3.5 a	51.9 ± 5.8 a
P value	<0.001	<0.001	—	<0.001	<0.001	<0.001

GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Values are mean ± SE.

Table 4. Average weekly respiration of CO_2 per gram of soil in different under-vine treatments over the course of six weeks.

	Cumulative CO_2 respiration (mg CO_2/g soil)			
Treatment	2011	2012	2013	2014
GLY	0.35 ± 0.02 b	1.46 ± 0.10 b	0.96 ± 0.04 b	0.67 ± 0.05 b
CULT	0.33 ± 0.02 b	1.42 ± 0.10 b	0.98 ± 0.05 b	0.70 ± 0.04 b
NV	0.48 ± 0.03 a	1.61 ± 0.10 ab	1.23 ± 0.06 a	0.96 ± 0.06 a
WC	0.44 ± 0.02 a	1.98 ± 0.12 a	0.94 ± 0.04 b	0.75 ± 0.05 b
P value	<0.001	0.001	<0.001	<0.001

GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Values are mean ± SE.

2012, CULT and NV TN concentrations were 79% and 80% lower than WC, respectively. Both CULT and NV leachate were 62% lower in TN than GLY. In 2013, CULT, NV, and WC had TN concentrations 81%, 86%, and 40% less than GLY, respectively. The TN concentration of CULT and NV leachate was 68% and 77% less than WC, respectively. In 2014, the TN concentration of CULT and NV leachate was 78% and 44% less than GLY, and 77% and 42% less than WC, respectively.

Similar to DOC leaching, TN leaching increased in the spring, beginning in April or May of each year (Fig. 2). The year 2012 exhibited two periods of high TN leaching from the WC treatment, in mid-April and from August through October. In 2013, there was a jump in TN leaching from GLY and WC in late June, while white clover did not account for a large proportion of vegetation in WC plots that year due to difficulty in establishment. There was another period of elevated TN leaching from the GLY plots in September through October of the same year.

Imidacloprid. Imidacloprid was found in either trace (<1 pbb) or in measurable (>1 pbb) concentrations in half or more of all samples over a 43-d period after imidacloprid application in 2012 (Table 7). In 2013, a large rainstorm with an accumulation of 54 mm on 8 Aug. and 22 mm on 9 Aug. removed most of the imidacloprid from the vineyard. Few detections of imidacloprid and no detections of its metabolites were recorded after these storms. Analysis of the 2013 data found no impact of treatment on leaching (data not shown).

In 2012, imidacloprid was found most frequently in GLY and NV, with almost every GLY and NV leachate sample testing positive for imidacloprid. CULT had the lowest number of positive test results, with only about half of CULT samples containing detectable imidacloprid. While nearly all GLY and NV leachate samples tested positive for trace amounts of imidacloprid or more, one-third of GLY leachate samples contained imidacloprid in measurable concentrations. In contrast, imidacloprid was not found in measurable concentrations in any NV samples. GLY had more samples with imidacloprid in measurable quantities than CULT and WC as well. GLY also had more samples with imidacloprid metabolites (imidacloprid des nitro HCL and or imidacloprid urea) than all other treatments.

Discussion

The implementation of different under-vine management practices over the course of 4 years impacted biological properties of soils as well as leachate composition. An impact of under-vine management on the physical structure of soil only became evident in the final year of the study.

In 2014, the bulk density of soil in the top 6 cm of CULT was greater than all other treatments. Compaction of soils through the disruption of soil structure from cultivation is one of the disadvantages of this practice (Lagacherie et al., 2006). The bulk density of CULT was above optimum ranges for field-crop production in clay-loam soils, and entering the spectrum where root elongation could become severely restricted (Reynolds et al., 2003). In addition to potential rooting problems, increased bulk density from soil compaction reduces the pore volume of soils, decreasing gas exchange and available water capacity (Archer and Smith, 1972). Consistent with these findings, measurements in soil porosity revealed that the top layer of CULT soil had lower total porosity than NV and WC and lower available water capacity than WC. Because these differences were found in the last year of the study, it is possible that this was the beginning of a long-term trend in soil physical structure associated with management practices. Because grapevines have one of the deepest rooting pattern distributions among plants (Smart et al., 2006), suppressed root growth in the top 6 cm of soils most likely would not drastically impact vine growth, but the other negative impacts of shallow soil compaction and reduced porosity may negatively impact the long-term health of the soil (Archer and Smith, 1972).

In addition to having greater porosity and water holding capacity, WC soils had greater soil organic matter than CULT in 2014. The decline in organic matter and porosity in CULT were likely connected since soil organic matter indicates the degree of soil aeration (Shukla et al., 2006). The physical action of cultivation makes many organic residues vulnerable to microbial attack and helps promote the loss of organic matter (Six et al., 1998). By not stimulating the metabolism of organic matter, and providing a greater input of organic materials, the WC cover crop promoted soils with more organic matter. Other vineyard studies have also found cover crops to increase soil organic matter in comparison with cultivation as well (Steenwerth and Belina, 2008).

Soil respiration rates are affected by substrate availability, soil moisture, and temperature (Sparling, 1997). In a laboratory setting, with controlled moisture and temperature, they are most reflective of the respiratory potential of the soil and the availability of biodegradable substrates, not necessarily of respiration rates occurring in the field (Doran and Safley, 1997). Measures of microbial activity are invaluable in that they respond quickly to changes in management practices, and can indicate changes in the flux of labile carbon before differences in soil organic matter can be detected (Sparling, 1997), which often take many years to become detectable (Smith, 2004). The decrease of labile carbon additions to soils, such as with herbicide use or tillage, has been shown to decrease soil microbial respiration rates (Cleveland et al., 2007). The general trend of greater soil respiration under the cover crops NV and WC than in the bare ground treatments GLY and CULT indicated that herbicide application and tillage were decreasing the input of biodegradable substrates to the soil, diminishing microbial activity, and potentially lowering soil organic

Table 5. Bulk density, penetration resistance, total porosity, and available water capacity in the top 6 cm of soils of different under-vine treatments.[z]

	Bulk density (g·cm^{-3})				Penetration resistance (MPa)			
Treatment	2011	2012	2013	2014	2011	2012	2013	2014
GLY	1.19 ± 0.07	1.26 ± 0.05	1.29 ± 0.04	1.34 ± 0.03 ab	0.44 ± 0.09	0.39 ± 0.03	0.52 ± 0.06	0.53 ± 0.05
CULT	1.21 ± 0.05	1.33 ± 0.03	1.33 ± 0.06	1.40 ± 0.03 a	0.40 ± 0.07	0.63 ± 0.08	0.58 ± 0.08	0.54 ± 0.04
NV	1.20 ± 0.03	1.22 ± 0.03	1.29 ± 0.03	1.28 ± 0.03 b	0.45 ± 0.13	0.61 ± 0.07	0.56 ± 0.04	0.50 ± 0.08
WC	1.25 ± 0.05	1.22 ± 0.06	1.27 ± 0.05	1.24 ± 0.02 b	0.48 ± 0.09	0.64 ± 0.13	0.53 ± 0.08	0.50 ± 0.06
P value	0.858	0.292	0.823	0.006	0.885	0.150	0.942	0.96
	Total porosity (% volume)				Available water capacity (% volume)			
Treatment	2011	2012	2013	2014	2011	2012	2013	2014
GLY	48.0 ± 1.9	39.1 ± 2.1	42.1 ± 1.8	42.0 ± 1.0 c	38.8 ± 2.3	35.4 ± 2.1	37.3 ± 1.6	36.9 ± 1.2 ab
CULT	48.0 ± 1.7	39.0 ± 1.2	41.5 ± 2.1	39.2 ± 1.0 bc	41.3 ± 1.9	36.1 ± 1.2	38.8 ± 2.0	35.6 ± 0.9 b
NV	49.8 ± 1.5	41.6 ± 1.0	43.4 ± 4.2	44.2 ± 1.4 ab	43.5 ± 2.1	38.8 ± 3.6	39.6 ± 1.2	38.6 ± 1.3 ab
WC	50.3 ± 1.8	41.5 ± 1.5	43.4 ± 2.9	46.6 ± 1.2 a	44.0 ± 0.7	38.0 ± 1.8	39.3 ± 2.5	40.3 ± 0.8 a
P value	0.715	0.459	0.900	0.001	0.219	0.412	0.822	0.023

GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Values are mean ± SE.
[z]Table has excluded macro, meso, and miscroporosity data, as well as data from 6- to 12-cm-depth soil cores, all of which did not find any significant differences between treatments. Data are available in the work of Karl (2015).

Table 6. Average annual dissolved organic carbon (DOC) and total nitrogen (TN) concentrations in leachate water samples from different under-vine groundcover treatments from 2011 to 2014.

	DOC (mg C/L)			
Treatment	2011	2012	2013	2014
GLY	13.77 ± 0.56 a	11.68 ± 0.47 a	12.17 ± 0.35 a	10.60 ± 1.01 ab
CULT	13.90 ± 0.62 a	11.38 ± 0.44 a	12.23 ± 0.48 a	10.13 ± 0.76 a
NV	9.31 ± 0.51 b	8.08 ± 0.55 b	9.78 ± 0.52 b	8.92 ± 0.88 b
WC	9.17 ± 0.35 b	8.59 ± 0.50 b	9.40 ± 0.48 b	6.49 ± 0.73 c
P value	<0.001	<0.001	<0.001	<0.001
	TN (mg N/L)			
Treatment	2011	2012	2013	2014
GLY	8.74 ± 1.18 a	9.36 ± 1.02 a	8.21 ± 1.07 a	7.39 ± 1.80 a
CULT	5.41 ± 0.93 b	3.59 ± 0.37 b	1.57 ± 0.19 c	1.65 ± 0.23 b
NV	3.59 ± 0.68 c	3.54 ± 0.55 b	1.11 ± 0.18 c	4.12 ± 1.42 b
WC	4.73 ± 0.63 b	17.37 ± 2.75 a	4.92 ± 1.12 b	7.10 ± 2.82 a
P value	<0.001	<0.001	<0.001	<0.001

GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Values are mean ± SE.

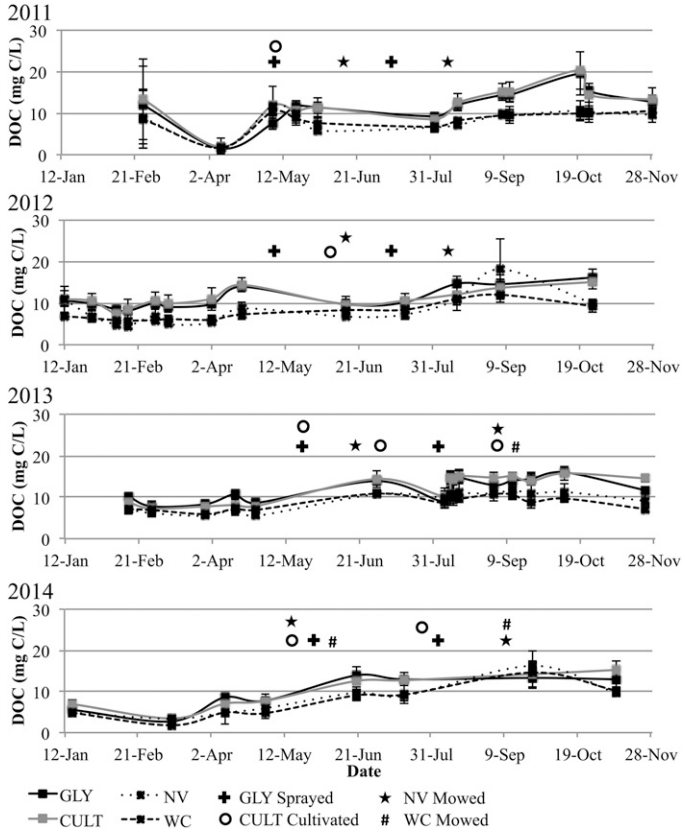

Fig. 1. Dissolved organic carbon concentrations (mg C/L) of leachate samples from under-vine groundcover treatments from 2011 to 2014. GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Concentrations are mean ± SE.

matter. Greater levels of microbial respiration are also associated with increased rates of nitrogen mineralization to plant available forms (Rustad et al., 2001). Increased rates of nitrogen mineralization can limit the need for fertilizers and soil amendments, as well as help diminish nitrogen competition of cover crops with grapevines.

DOC is an important source of carbon, nitrogen, phosphorous, and sulfur for soil microbial metabolism, and influences the physical, chemical, and biological properties of soil (Haynes and Beare, 1996). Because much of it is bound to or incorporated within soil aggregates, disturbance of the soil structure and increased erosivity of soils are reported to increase the leaching of DOC to surface and below-groundwater bodies (Amezketa, 1999; Brye et al., 2001; Kalbitz and Park, 2000). Plant cover, as well as greater microbial activity, has also been linked with immobilizing DOC, and preventing its leaching (Qualls and Richardson, 2003; Tripolskaja et al., 2013). The pattern of greater DOC leaching from GLY and CULT soils in comparison with NV and WC soils is consistent with these reports that less disturbed soils with more cover limit DOC leaching. Leaching of DOC out of the soil is indicative of carbon loss from the agroecosystem. It has been suggested that increases in DOC from changes in land management could be used, similarly to microbial biomass and respiration, as early indicators of soil organic matter loss (Silveira, 2005).

Under-vine treatments also impacted TN leaching of soils throughout the study. There was a general trend of greater nitrogen leaching in GLY and WC treatment soils than in CULT and NV. Other vineyard groundcover studies have found greater nitrogen leaching in herbicide-treated under-vine rows than in cultivated treatments (Steenwerth and Belina, 2010). A greater presence of soil carbon, microbial biomass, and plant residues has been associated with reduced nitrogen leaching in cropping systems (Kramer et al., 2006; Steenwerth and Belina, 2008). It is likely that the relative absence of plant cover and associated root systems in the GLY treatment in comparison with CULT and NV treatments reduced the immobilization of nitrogen (Weinert et al.,

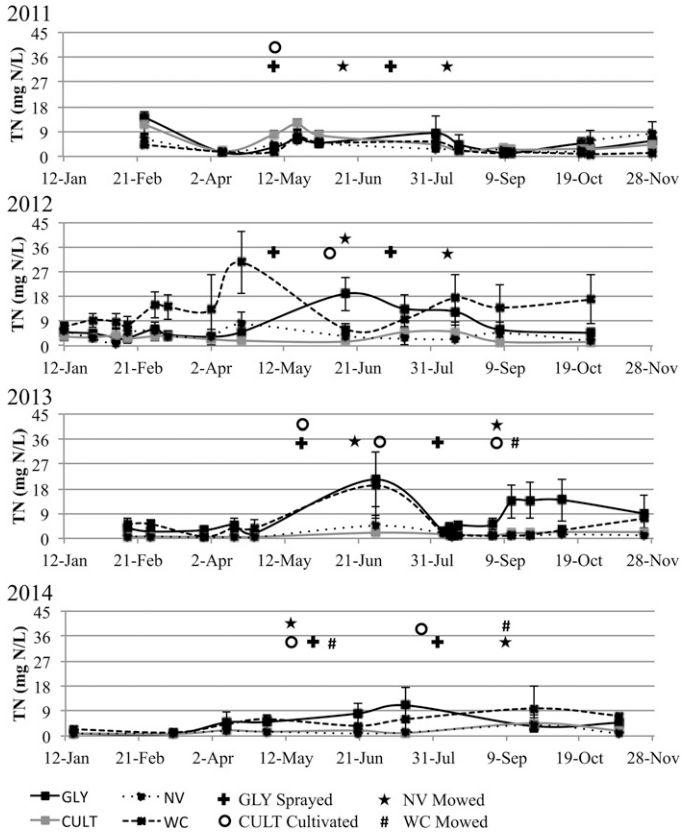

Fig. 2. Total nitrogen concentrations (mg N/L) of leachate samples from under-vine groundcover treatments from 2011 to 2014. GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover. Concentrations are mean ± SE.

Table 7. Percent of leachate samples with imidacloprid found in trace (<1 pbb) or measurable (>1 pbb) concentrations, measurable concentrations, and either trace or measurable concentrations of two imidacloprid metabolites: imidacloprid des nitro HCl or imidacloprid urea.

Treatment	% Samples with trace or measurable imidacloprid detections	% Samples with measureable imidacloprid concentrations	% Samples with imidacloprid metabolites
GLY	93.3 a	33.3 a	40.0 a
CULT	50.0 b	5.6 b	5.6 b
NV	94.1 a	0.0 b	0.0 b
WC	68.8 ab	6.3 b	6.3 b
P value	0.004	0.016	0.013

GLY = glyphosate, CULT = cultivation, NV = native vegetation, WC = white clover.

2002). The greater nitrogen leaching in the WC treatment can be attributed to the decomposition of nitrogen rich clover tissue, which has been observed in other cover crop studies (McCracken et al., 1994). The high concentrations of TN in the WC treatment in Apr. 2012 can likely be attributed to the decomposition of clover tissue from 2011 following the thawing of the soil. Greater leaching of nitrate can lead to increased emissions of nitrous oxide, a powerful greenhouse gas, from agricultural soils (Steenwerth and Belina, 2010), as well as entering local bodies of water. However, it is important to note that the lysimeters in this study did not record the volume of leachate passing through them, and therefore total volumes of DOC and TN were not calculated, just their concentrations.

In addition to providing insight about the movement of DOC and TN in the vineyard under different under-vine ground management treatments, there was an observed impact of groundcover management on imidacloprid insecticide movement and persistence within the vineyard. Over the course of 43 d, after imidacloprid was applied to the vines, it was found in at least half of all leachate samples, regardless of treatment, and in nearly all NV and GLY samples. However, imidacloprid and its breakdown metabolites were found in greater concentrations in GLY treatment leachate, than in other treatments. The lack of plant cover in the GLY treatment may have introduced more imidacloprid directly to the soil (through dripping from vine foliage) where it was not absorbed by plants, helping explain why imidacloprid was found in higher concentrations, and its metabolites detected more frequently in GLY treatment than in other treatments (Goulson, 2013). Testing groundcover vegetation for concentrations of imidacloprid and its metabolites would have helped elucidate the movement of these chemicals through the agroecosystem. Krupke et al. (2012) found imidacloprid in nontarget vegetation in the borders of fields planted with imidacloprid-treated row crops in concentrations as high as 9 pbb.

The degradation of imidacloprid within soils is dependent on microbial activity (Liu et al., 2011). Additionally, imidacloprid has a high leaching potential, which increased with greater concentrations of DOC in leachate water due to greater competition for sorption sites on soil particles (Flores-Céspedes et al., 2002). More of the imidacloprid that entered soil may have been leached from GLY plots than in the NV and WC treatments, due to lower microbial activity and/or greater DOC concentrations in GLY. Preferential macropore flowpaths from soil cracking in GLY may have increased the leaching of imidacloprid as well; soil cracking from persistent herbicide application has been associated with more rapid and increased rates of nitrate and benomyl fungicide leaching in similar soil types to those in our study (Merwin et al., 1996). Imidacloprid also resists leaching by sorbing to organic matter in the soil (Cox et al., 1998). If rapidly transported through the soil column though soil cracks, which we observed in the GLY treatment, imidacloprid leaching may have increased due to fewer opportunities to sorb to soil particles. Imidacloprid is highly toxic to many aquatic and soil-dwelling invertebrates (Cox, 2001; Stoughton et al., 2008), making the reduction of imidacloprid leaching by preventing its contact with bare soil a priority. However, if imidacloprid is absorbed or taken up by groundcover vegetation, including flowering cover crops such as white clover, it may prove problematic for nontarget organisms, such as honeybees, *Apis mellifera* L., whose foraging and homing ability can be reduced by ingesting sublethal doses of imidacloprid from pollen and nectar sources (Yang et al., 2008).

Conclusion

Management practices that maintain soil quality are paramount for the long-term sustainability of a vineyard. Over a relatively short period, herbicide application and cultivation displayed trends suggesting that these practices are diminishing soil organic matter and microbial activity within vineyard soils in comparison with cover crop treatments. Preserving soil organic matter is crucial for maintaining the physical, chemical, and biological functions of a healthy soil. The increased leaching of DOC from CULT and GLY treatments, in addition to removing more carbon from these vineyard soils, also poses as a potential source of contamination to the local watershed, as does leaching of imidacloprid from GLY soils. However, potential absorption of imidacloprid by ground vegetation may pose a threat to nontarget insects. Cumulatively, these factors demonstrate the potential of under-vine cover crops to maintain soil quality and decrease the leaching of nutrients and agrochemicals in vineyards in comparison with conventional practices.

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