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Biochar–compost mixture and cover crop effects on soil carbon and nitrogen dynamics, yield, and fruit quality in an irrigated vineyard

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Abstract

Effects of biochar–compost (B+Com) mixture and cover crop were assessed on soil and grapevine productivity in an irrigated Merlot (*Vitis vinifera* L.) vineyard in Okanagan Valley, British Columbia (BC), Canada, from 2017 to 2020. The experimental design was a factorial arrangement of control, B+Com, cover crop, and combination of cover crop and B+Com (cover crop/B+Com) treatments in alleys with four replications. The B+Com comprised a 1:1 ratio of biochar and compost and was applied at a rate of 22 Mg ha^{-1} dry weight basis in May 2017 and 2019. The cover crop consisted of a dryland forage mixture and bird's-foot trefoil (*Lotus corniculatus* L.). B+Com treatment did not affect cover crop biomass or tissue C and N concentrations except for a 12% reduction in 2019 biomass. B+Com and cover crop/B+Com increased soil C content averaged across sampling dates by 11% and 17% ($P < 0.05$), respectively, only at the 0–15 cm soil depth compared with the control. Cover crop treatment did not affect ($P < 0.05$) soil C content at two soil depths in all sampling dates. Soil N content was not affected by B+Com, decreased by an average of 12.5% at both soil depths with cover crop, and increased with cover crop/B+Com by 4% only at the 0–15 cm soil depth averaged across sampling dates ($P < 0.05$). Grape yield was increased by 32% by cover crop/B+Com relative to control only in 2020. The cover crop reduced petiole N and pruning weights in one or two years out of three.

Key words: biochar, carbon sequestration, fruit quality, yield

Résumé

De 2017 à 2020, les auteurs ont évalué les effets d'un mélange de biocharbon et de compost (B+Com) et d'une culture-abri sur la productivité du sol et du raisin dans le vignoble irrigué d'un cépage Merlot (*Vitis vinifera* L.) de la vallée de l'Okanagan, en Colombie-Britannique (Canada). L'expérience portait sur un agencement factoriel des traitements suivants : témoin, B+Com, culture-abri (CA), culture-abri et B+Com (CA/B+Com). Les traitements ont fait l'objet de quatre réplications dans les rangs. Le traitement B+Com consistait en l'application de biocharbon et de compost dans un rapport 1:1, à raison de 22 Mg de poids sec par hectare, en mai 2017 et 2019. La couverture-abri se composait d'un mélange de plantes fourragères pour l'aridoculture et de lotier corniculé (*Lotus corniculatus* L.). Le traitement B+Com n'a pas modifié la biomasse de la culture-abri, ni la concentration de C et de N dans les tissus, mais les auteurs ont relevé une baisse de 12 % de la biomasse en 2019. Aux dates d'échantillonnage, le traitement B+Com et le traitement CA/B+Com ont accru la teneur moyenne en C du sol de 11 et de 17 % ($P < 0{,}05$), respectivement, mais uniquement à la profondeur de 0 à 15 cm, comparativement au traitement témoin. La culture-abri n'a eu aucune incidence ($P < 0{,}05$) sur la teneur en C du sol aux deux profondeurs examinées, peu importe la date des prélèvements. Le teneur en N du sol n'a pas été affectée par le traitement B+Com, a diminué d'en moyenne 12,5 % aux deux profondeurs avec la culture-abri et a augmenté d'en moyenne 4 % par rapport au traitement témoin, à la profondeur de 0 à 15 cm, avec le traitement CA/B+Com ($P < 0{,}05$), aux dates d'échantillonnage. Comparativement au traitement témoin, le traitement CA/B+Com a accru le rendement du raisin de 32 %, mais uniquement en 2020. La culture-abri a réduit la concentration de N dans le pétiole et le poids les parties élaguées, une ou deux années sur les trois qu'ont duré l'expérience. [Traduit par la Rédaction]

Mots-clés : biocharbon, séquestration du carbone, qualité du fruit, rendement

Introduction

Grape (*Vitis vinifera* L.) is the largest fruit crop globally with about 80% of the harvested fruits used for wine making (Dominguez et al. 2014). Despite an increase in consumer willingness to pay a premium price for sustainable wine and stricter environmental regulations, producing wine with minimum or no agrochemicals is challenging, particularly when it comes to pest control and fertilization (Reeves 1997). Soil organic amendments and cover crops are proposed as alternatives to overcome this challenge (Messiga et al. 2015). Biochar's unique structural and physical characteristics make it a good candidate for supporting establishment and growth of cover crops in vineyards (Baronti et al. 2014). When biochar is blended with compost, it has the potential to supply nutrients to both vine and cover crops over time (Schmidt et al. 2014). Limited studies explored the single and interactive effects of biochar–compost (B+Com) and cover crop on vineyard's soil organic carbon (C) and total nitrogen (N) contents, grape yield, and fruit quality. B+Com and cover crops may improve the sustainability of wine grape production through enhanced biodiversity, improved water holding capacity, increased soil organic C and total N contents, and improved yield and fruit quality (Baronti et al. 2014; Genesio et al. 2015; Maienza et al. 2017).

Biochar is reported to enhance soil structure, improve nutrients and water retention capacity (Genesio et al. 2015), provide habitat for soil micro-organisms, control soil acidity, and help mitigate climate change by reducing the amount of nitrous oxide emitted and contributing to the sequestration of C in vineyard's soils (Baronti et al. 2014; Ok et al. 2015). The positive role of biochar in regulating water availability in the vineyard in the presence of cover crops was reported in Mediterranean climates (Baronti et al. 2014; Genesio et al. 2015). However, fresh biochar is nutrient poor, which leads to soil nutrient immobilization, particularly N (Meyer et al. 2014). Blending compost with biochar (charged biochar) during the process or after the process of composting reduces subsequent C and N losses (Meyer et al. 2014; Meyer-Kohlstock et al. 2015) and enhances C sequestration (Niehues 2015). Application B+Com in vineyards was found to increase soil organic C, supply nutrients, and enhance soil biological activities with no adverse effect on crop yield or fruit quality (Bustamante et al. 2010; Burg et al. 2019; Döring et al. 2019; Safaei Khorram et al. 2019). Sánchez-Monedero et al. (2019) found that B+Com increased grape yield, fruit quality, and titratable acidity, but reduced total soluble solid content in Friuli Venezia Giulia, Italy. Studies on the use of B+Com in temperate region vineyards are rare.

Previous studies reported positive effects of cover crops on wine grape yield and fruit quality (i.e., soluble solids) and soil function and encouraged the use of cover crops in vineyards (Olmstead et al. 2001; Messiga et al. 2015). The cover cropping practice provides several benefits such as supplying nutrients (Novara et al. 2013), enhancing C sequestration (Curtis 2013; Poeplau and Don 2015; Kaye and Quemada 2017), improving water infiltration and conservation (Celette and Gary 2013; Ruiz-Colmenero et al. 2013; Medrano et al. 2015), improving biological control (Sáenz-Romo et al. 2019), stimulating microbial activity and diversity (Peregrina et al. 2012), and reducing erosion (Marques et al. 2010; Tompkins 2010). Cover crops change water and N dynamics (Celette and Gary 2013) and drive the vine root distribution towards deeper soil more localized to vine row (Celette et al. 2008). Cover crops suppress weeds by competing for resources and creating a physical barrier (Fredrikson et al. 2011). By introducing cover crops into alleys in vineyards, consideration should be given to potential competition with the vines (Celette and Gary 2013; Curtis 2013). Despite several benefits of cover crops, some growers are still hesitant to use cover crops due to this potential competition for water and nutrients. Application of B+Com in vineyard's alleys where cover crops are sown has the potential to reduce the risk of competition between grapevines and cover crops by improving soil water holding capacity (Karhu et al. 2011; Baronti et al. 2014) and enhancing soil nutrient retention (Clough et al. 2013).

The overall goal of this study was to examine the effect of an alley cover crop with or without B+Com on soil C sequestration and wine grape productivity in an irrigated Merlot vineyard located in the semi-arid Okanagan Valley, BC, Canada. With limited literature information available on the effect of cover crops in combination with B+Com, we hypothesized that (*i*) B+Com application in the vineyard's alleys has a positive effect on cover crop biomass and consequently on cover crop-driven C and N, (*ii*) sowing cover crop in the vineyard's alleys will increase soil organic C and total N in 0–30 cm soil depth, and (*iii*) B+Com application or sowing cover crop in the vineyard's alleys or their interactions will positively affect vine growth, grape yield, fruit quality, and vine N status. Therefore, specific objectives of the study were to determine the effects of B+Com or cover crop or their combination on (*i*) soil organic C and total N contents in 0–15 and 15–30 cm soil depth, (*ii*) cover crop biomass, and (*iii*) grape yield and fruit quality. The output of this study was to provide recommendations on utilization of B+Com and cover crop for improving or sustaining the grapevine productivity in light-textured soils of Okanagan Valley, BC, Canada vineyards.

Materials and methods

Experimental site

The experimental site was located in the south-central Okanagan Valley (49°33′59″N, 119°38′12″W) at the Summerland Research and Development Centre of Agriculture and Agri-Food Canada, Summerland, BC, Canada. The area is characterized by cool winters (mean December–February temperature: −0.5 °C), warm summers (mean June–August temperature: 20.0 °C), and low annual precipitation (346 mm year^{-1}; Environment and Climate Change Canada 2020) (Table 1). The experiment was located on south–south-west-facing slope in a Skaha loam (Brown Chernozemic soil) (Wittneben 1986; Soil Classification Working Group 1998). More details about the experimental site were described by Hannam et al. (2016*b*).

The grape block was established in May 2011 with Merlot grape variety (clone 181 on SO4 rootstock) according to standard industry practices. Plots comprised 5 vines including a guard vine on either end and 3 experimental vines. Vines were planted 1.2 m apart in row and 3.0 m spacing between the rows, resulting in a density of 2778 vines ha^{-1}. General maintenances were performed according to Best Practices Guide by British Columbia Wine Grape Council (Best Practices Guide | BCWGC 2010). There was no N fertilizer application to vineyard's alleys prior to the experiment or during the

Table 1. Monthly precipitation and mean temperatures for 2017–2020 and average 30-year normals at Summerland Research and Development Centre, Summerland, British Columbia, Canada (Environment and Climate Change Canada 2020).

Month	2017	2018	2019	2020	30-year average (1981–2010)
Precipitation (mm)					
April	53.6	40.4	13.4	8.4	26
May	85.2	27.0	13.0	59.6	39.3
June	19.9	36.0	25.1	61.8	46.3
July	0.0	14.0	38.9	12.3	28.7
August	0.0	3.2	36.5	17.0	28.3
September	9.4	40.2	85.3	8.5	24.6
October	10.8	48.4	12.9	51.9	26.0
April–September	179	209	225	219	219
Mean temperature (°C)					
April	8.3	8.7	9.2	8.7	9.4
May	14.2	17.4	16.3	13.9	14.1
June	18.0	17.8	18.5	16.5	17.6
July	23.8	22.5	20.6	21.0	21.4
August	22.6	21.2	21.6	21.9	21.0
September	16.9	14.1	15.7	17.9	16.0
October	8.3	8.0	7.3	8.7	9.0
April–September	16.0	15.6	15.6	15.5	15.5

experiment. The fertilizer N rate for the vine rows since the project establishment was 40 kg N ha^{-1} year^{-1}. A dual irrigation system was used from 2017 to 2020: drip irrigation in vine rows and understory sprinklers for alleys. Drip emitters were placed at 0.3 m on both sides of each vine (two 4 L h^{-1} emitters per vine) and were designed to replace 100% of water lost to evapotranspiration. Cover crops in alleys were mowed twice per each growing season when reaching 30 cm height. To control the weed growth under the vine, a 0.75 m strip on both sides of the vine row was sprayed with glyphosate 3 times per growing season.

Grapevine alleys with or without cover crop and/or B+Com were arranged in a randomized complete block design with 4 replications. Treatments included control, B+Com, cover crop, and cover crop with B+Com (cover crop/B+Com). Each alley treatment was comprised 2 alleys on both sides of a row. Therefore, every other row of vines was considered a guard row. The B+Com treatment consisted of a 1:1 ratio of biochar and compost that was blended 3 weeks before application and hand applied at a rate of 22 Mg ha^{-1} on a dry weight basis every other year (May 2017 and May 2019) to the respective alleys before sowing of the cover crop. The B+Com was mixed with the top 5–7 cm soil using a rotor tiller. The application rate was based on recommendations from Schmidt et al. (2014) and Karhu et al. (2011). Certified organic biochar was purchased from Canadian AgriChar Company in Maple Ridge, British Columbia. The feedstock for the biochar was wood chips primarily from *Pinus contorta* var. latifolia, *Picea glauca*, and *Pseudotsuga menziesii*, and the pyrolysis temperature was 500 °C. The compost was a year old and composed of 15% grape pomace, 20% straw, 25% shredded bark and wood chips, and 40% cow manure obtained from BigHorn Composting Company, Penticton, British Columbia. No inorganic fertilizers were applied in the alleys. The total N applied through B+Com application during the experiment was 24.8 Mg N ha^{-1}. Biochar, compost, and B+Com characteristics are summarized in Table 2.

The cover crop mixture was a commercially available southern interior dryland forage mixture of 20% slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners), 10% Proper orchardgrass (*Dactylis glomerata* L.), 10% TL dryland Porto orchardgrass, 20% Oracle creeping red fescue (*Festuca rubra* L.), 20% tetraploid common annual ryegrass (*Lolium multiflorum* L.), 10% Kirkcredted wheatgrass (*Agropyron cristatum* L.), and 10% creeping alfalfa (*Medicago sativa* L.) (https://www.tlhort.com/images/files/docs//ta_223_southern_interior_dryland.pdf) sown at a rate of 22.4 kg ha^{-1} plus bird's-foot trefoil (*Lotus corniculatus* L.) sown at a rate of 6.7 kg ha^{-1}. These seeding rates were recommended by the seeding company. The cover crop was initially seeded in spring 2017 and reseeded in spring 2019. Southern Interior Dryland mix is designed for non-irrigated pasture or hay regions of the southern British Columbia interior. The weeds in control and B+Com treatments were controlled by glyphosate only in 2018, and no glyphosate was applied to cover crop in 2017 and 2019.

Cover crop biomass and C and N content

Cover crop samples were collected before each mowing using a 0.25 m^2 quadrate per alley section of each plot (2

Table 2. Mean biochar and compost chemical characterizations used in 2017 and 2019.

Parameter	Unit	Biochar	Compost	Biochar–compost mixture
Moisture	%	26.7 (0.65)	78.1 (3.71)	50.3 (4.21)
EC	μS cm^{-1}	121 (0.03)	144 (0.02)	130 (0.05)
pH	—	10.5 (0.04)	8.67 (0.03)	9.17 (0.07)
Organic C	%	58.2 (0.43)	26.7 (1.24)	30.7 (1.80)
Total N	%	0.44 (0.02)	1.37 (0.11)	1.06 (0.09)
P	%	0.487 (0.01)	0.301 (0.02)	0.358 (0.03)
K	%	3.82 (0.14)	1.57 (0.16)	1.94 (0.13)
S	%	0.401 (0.03)	0.127 (0.01)	0.169 (0.01)
Ca	%	5.51 (0.08)	1.29 (0.06)	2.30 (0.16)
Mg	%	1.03 (0.02)	0.349 (0.003)	0.511 (0.02)
Fe	%	0.628 (0.02)	0.817 (0.04)	0.838 (0.04)
Zn	mg kg^{-1}	325 (5.20)	68.0 (2.15)	135 (8.06)
Mn	mg kg^{-1}	2387 (39.9)	305 (3.89)	868 (57.3)
Cu	mg kg^{-1}	55.1 (0.84)	27.1 (0.92)	37.4 (2.37)
B	mg kg^{-1}	106 (2.12)	34.7 (1.69)	53.4 (4.24)
Mo	mg kg^{-1}	6.86 (0.76)	9.43 (0.70)	10.1 (0.64)
Na	%	0.194 (0.005)	0.028 (0.001)	0.064 (0.003)
Al	%	0.531 (0.01)	0.393 (0.01)	0.494 (0.01)
Ag	mg kg^{-1}	1.18 (0.01)	0.040 (0.000)	0.360 (0.05)
As	mg kg^{-1}	7.57 (0.12)	1.24 (0.08)	3.42 (0.31)
Ba	mg kg^{-1}	686 (10.4)	64.2 (1.49)	255 (26.8)
Be	mg kg^{-1}	0.059 (0.003)	0.103 (0.005)	0.105 (0.001)
Cd	mg kg^{-1}	2.18 (0.04)	0.153 (0.007)	0.762 (0.07)
Co	mg kg^{-1}	5.36 (0.33)	4.67 (0.29)	5.52 (0.17)
Cr	mg kg^{-1}	117 (17.9)	276 (21.8)	284 (19.7)
Ni	mg kg^{-1}	62.5 (8.63)	147 (12.1)	153 (11.2)
Pb	mg kg^{-1}	8.50 (0.12)	3.49 (0.24)	5.45 (0.45)
Sb	mg kg^{-1}	0.366 (0.04)	0.036 (0.002)	0.131 (0.01)
Se	mg kg^{-1}	0.836 (0.05)	0.148 (0.01)	0.308 (0.02)
V	mg kg^{-1}	12.2 (0.34)	16.3 (0.65)	17.5 (1.14)

Note: Standard errors are reported in brackets (n = 8). Ag, argentum; Al, aluminum; As, arsenic; B, boron; Ba, barium; Be, beryllium; Ca, calcium; Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper; EC, electrical conductivity; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Mo, molybdenum; N, nitrogen; Na, sodium; Ni, nickel; P, phosphorus; Pb, plumbum; S, sulfur; Sb, antimony; Se, selenium; V, vanadium; Zn, zinc; SD, standard deviation.

quadrates per plot). Cover crop comprised >80% of the total vegetative ground cover in the alleys determined by quadrate percentage coverage and were mowed, as part of the typical management practice in this vineyard, in July and after harvest. The mowed clippings were not removed from plots, except for clippings in the quadrates. The aboveground biomass in each quadrant was cut at 2.5 cm above the soil surface, stored on ice in coolers for transfer, and fresh weighed within 3 h. The biomass samples were immediately dried at 60 °C until they reached a constant weight. Oven-dried samples were weighed, ground with a Thomas Wiley mill (Thomas Scientific) followed by ball milling. Tissue C and N concentrations were measured using a LECO 628 (LECO Corporation, St. Joseph, MI). Cover crop C and N contents were calculated by multiplying dry biomass, and tissue C and N concentrations.

Soil and biochar compost

To establish a baseline for soil properties, composite soil samples consisting of eight sub-samples were collected from each replication at the 0–15 and 15–30 cm soil depths using soil probe with 2.5 cm diameter in May of 2017 before B+Com application or cover crop sowing. For each plot, soil samples were collected from alleys on both sides of the grape vine row. Soil samples were immediately air-dried and passed through a 2 mm sieve. The pH and electrical conductivity (EC) were measured in 1:2 ratio soil:0.01 N $CaCl_2$ with pH and EC electrodes. Mehlich-III extractable macro- and micronutrients were measured by an ICP-OES (Spectro Analytical Instruments, Kleve, Germany). Organic C (after carbonate removal with HCl 1.0 N) and total N were determined using a LECO 628 CHN analyzer (LECO Corporation, St. Joseph, MI). Carbon sequestration and soil N gain values were calculated

Table 3. Mean soil characteristics in alley location at the 0–15 and 15–30 cm depths before start of the experiment in October 2016.

Parameter	Unit	0–15 (cm)	15–30 (cm)
Sand	%	48.5 (0.93)	47.6 (0.83)
Silt	%	34.5 (0.57)	35.0 (0.50)
Clay	%	17.0 (0.43)	17.3 (0.43)
EC	μS cm^{-1}	167 (15.0)	101 (8.00)
pH	—	7.04 (0.13)	7.18 (0.07)
Organic C	g kg^{-1}	17.8 (0.40)	7.80 (0.20)
Total N	g kg^{-1}	1.52 (0.10)	0.63 (0.01)
P	mg kg^{-1}	57.0 (10.7)	38.9 (9.53)
K	mg kg^{-1}	221 (22.7)	123 (9.40)
S	mg kg^{-1}	14.3 (1.27)	11.4 (0.63)
Ca	mg kg^{-1}	2058 (96.3)	1910 (67.0)
Mg	mg kg^{-1}	305 (17.7)	272 (6.67)
Fe	mg kg^{-1}	98 (5.90)	88 (3.97)
Zn	mg kg^{-1}	11.9 (1.27)	5.8 (0.67)
Mn	mg kg^{-1}	96 (3.33)	77 (3.23)
Cu	mg kg^{-1}	5.76 (0.10)	5.54 (0.07)
B	mg kg^{-1}	1.89 (0.10)	1.29 (0.07)

Note: Standard errors are reported in brackets ($n = 9$). B, boron; Ca, calcium; Cu, copper; EC, electrical conductivity; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; N, nitrogen; P, phosphorus; S, sulfur; Zn, zinc; SD, standard deviation.

for the period of 39 months from the first application of the B+Com on 10 May 2017 to the last soil sampling on 14 August 2020. Particle size distribution was determined by laser analyzer with H_2O_2 pretreatment (Konert and Vandenberghe 1997). Soil texture was loam and soil developed on calcareous parent materials. Soil properties are reported in Table 3.

Composite soil samples, each consisting of eight subsamples, were collected from the 0–15 and 15–30 cm depths at alley (intra-row) location for determination of soil organic C and total N concentrations in June 2017, May 2018, May 2019, and Aug 2020. Soil organic C and total N concentrations were determined as previously described. At the same time as soil sampling, another set of soil samples was taken to determine bulk density at 0–15 and 15–30 cm using 5 cm inner diameter cores. The soil was oven-dried at 105 °C for 24 h to determine bulk density.

Four composite samples of each biochar, compost, and their mixture (1:1 ratio) were air-dried and finely ground using a ball mill, then re-dried at 60 °C for 2 h and their chemical properties were determined. Biochar and compost pH and EC were measured in a 1:2 ratio of amendment to water by pH and EC electrodes. Amendments' organic C and total N were determined by the same procedure as for soil.

Yield, fruit quality, growth, and leaf petiole N concentration

Grape clusters were harvested in late October from 2018 to 2020. The 2017 yield was lost due to severe animal damage. The grape yield was determined by harvesting clusters on the 3 innermost vines of each plot with a set of harvesting pruners. Harvested clusters were counted and weighed. The average cluster weight was calculated by dividing the total weight of clusters per plot by the number of clusters. After harvest, a representative sub-sample of 12 fruit clusters was weighed and berries were plucked from the upper, middle, and lower third of each cluster for a total of 216 berries. The 216 berries were weighed to determine average berry weight. Berries were crushed by hand and the juice was immediately filtered through several layers of cheesecloth to remove skins and seeds in preparation for analysis. The filtrate was measured for pH and titratable acidity, expressed as grams per litre tartaric acid determined by automated titration with 0.1 mol/L NaOH to an endpoint pH of 8.1. Soluble solid concentration (Brix) was determined by refractometry using Cole-Parmer digital refractometer. The concentration of yeast assimilable N was determined on 15 mL juice samples using the formal titration method (Gump et al. 2001). Vines were pruned in the dormant season, between late February and late April, and pruned materials were weighed to assess canopy growth and vine balance.

Petiole samples were collected at veraison. Samples were taken from the sixth or seventh leaf from the cane tip; if there was a cluster at the sixth or seventh leaf, it was taken directly across from the cluster. Ten petioles were collected from each of the three data vines from each plot and placed in bags on ice until transported. Petiole samples were then weighed and dried in an oven at 60 °C for 48 h. Samples were finely ground using a ball mill, and stored until analyses for N using a LECO 628 (LECO Corporation, St. Joseph, MI).

Statistical analysis

Data were analyzed with JMP software (SAS Institute, Inc., V.15.0.0). The normality of data distribution was tested with Shapiro–Wilk test. When normality could not be assumed, data were transformed. Data transformation was performed on yield (square root), total cluster number (square root), and soluble solids (log). Data were analyzed using a two-way Analysis of variance (ANOVA) by considering B+Com and cover crop as fixed factors, and year and replications as random factors. As the effect of soil depth was always significant on soil C and N content at each sampling date with no interactions with other factors, soil depth was not included in the analysis as a factor. The exception was cover crop parameters in 2018, where a one-way ANOVA was used as weeds in non-cover cropped alleys controlled by glyphosate application. When a treatment's effect on a parameter was significant, differences between treatment means were evaluated using the Tukey's HSD test at a significant level of $P < 0.05$. Only significant differences at $P < 0.05$ reported decrease or increase in the "Results" section.

Results

Cover crop biomass and C and N content

Cover crop biomass and C and N contribution to soil were measured from 2017 to 2019 in vineyards alleys (Table 4). In 2017, vegetative ground cover generated 5.67 Mg ha^{-1} dry biomass and contributed 2.18 Mg C ha^{-1} and 0.15 Mg N ha^{-1}, but was not affected by B+Com or cover crop treatments.

Table 4. Mean values and ANOVA for the effect of biochar–compost (B+Com) and cover crop treatments on total dry biomass of weeds or cover crop+weeds in alleys, and their C and N concentrations and contents from 2017 to 2019.

Treatment		Total dry biomass (Mg ha^{-1})	Average tissue C concentration (%)	Average tissue N concentration (%)	Biomass C content (Mg ha^{-1})	Biomass N content (Mg ha^{-1})	Average tissue C/N ratio
2017							
Control		6.12	40.37	3.33	2.20	0.18	12.17
B+Com		5.23	39.92	3.40	2.07	0.17	11.87
Cover crop		5.67	40.05	2.66	2.28	0.15	15.05
Cover crop/B+Com		7.14	39.72	2.85	2.83	0.21	14.12
SEM		0.87	0.18	0.11	0.35	27.85	0.44
Source of variation	df	*P* value					
B+Com	1	NS	*	NS	NS	NS	NS
Cover crop	1	NS	NS	***	NS	NS	***
B+Com × cover crop	1	NS	NS	NS	NS	NS	NS
2018[a]							
Cover crop		5.82	42.7	2.66	2.486	0.143	14.2
Cover crop/B+Com		5.45	42.9	2.65	2.342	0.136	14.7
SEM		0.043	0.35	0.15	0.15	0.009	0.62
Source of variation	df	*P* value					
B+Com	1	NS	NS	NS	NS	NS	NS
2019							
Control		1.50	36.5	2.61	0.556	0.037	14.5
B+Com		0.93	36.3	2.74	0.347	0.024	13.6
Cover crop		7.20	37.9	2.13	2.86	0.147	18.2
Cover crop/B+Com		6.69	37.6	1.93	2.68	0.134	19.7
SEM		0.23	0.38	0.11	0.089	0.052	0.827
Source of variation	df	*P* value					
B+Com	1	*	NS	NS	NS	*	NS
Cover crop	1	***	NS	NS	NS	***	NS
B+Com × cover crop	1	NS	NS	NS	NS	NS	NS

Note: df, degree of freedom; SEM, standard error mean; ***, **, *, significant at $P \leq 0.001$, 0.01, and 0.05, respectively; NS, non-significant at $P \leq 0.05$.; SEM, standard error mean; alley ground vegetative covers were sampled 2 times in each season and presented means are the 2 samplings' sum for biomass and contents and average for concentrations.
[a]Weeds in control and B+Com treatments were sprayed with glyphosate in 2018; therefore, no groundcover biomass data for these treatments are reported in 2018.

The vegetative ground cover C concentrations in 2017 were about 1% lower in B+Com treatment, but were not affected by cover crop treatment or interactions. The vegetative ground cover N concentrations were about 18% lower in cover crop treatment compared with control, but were affected by B+Com or interactions in 2017. Averaged across control and B+Com treatments, cover crop generated 5.63 Mg ha^{-1} year^{-1} dry biomass and contributed 2.41 Mg C ha^{-1} year^{-1} and 0.140 Mg N ha^{-1} year^{-1} in 2018. In 2019, groundcover vegetation dry biomass and biomass N content were significantly affected by B+Com or cover crop treatments. Dry biomass was 12.4% lower in amended relative to non-amended treatment and was 4.69 times greater in cover crop compared with non-cover cropped treatments in 2019. Biomass N content was reduced by 28% in amended compared with non-amended treatment, and was greater by 3.58 times in cover crop compared with non-cover cropped treatments in 2019. Biomass C and N concentrations and biomass C content were not affected by any of the treatments or their interactions in 2019.

Soil C and N content

Across all sampling dates, B+Com alone or in combination with cover crop significantly increased the soil C content only at the 0–15 cm soil depth compared with the control by 11% and 17%, respectively (Table 5). Cover crop treatment did not affect soil C content at the 0–15 or 15–30 cm soil depths in all sampling dates. The B+Com did not affect soil N content, while cover crop decreased soil N content in both soil depths by 8%–17% and cover crop/B+Com increased the soil N content only at the 0–15 cm soil depth by 4% across all sampling dates (Table 5). Overall, over the period of 39 months, organic C increased in vineyard's alleys by 2.3 times from 0.62 Mg ha^{-1} in control to 1.42 Mg ha^{-1}

Table 5. Mean values and ANOVA for the effect of biochar–compost (B+Com) and cover crop treatments on soil organic C and total N content in alleys at the 0–15 and 15–30 cm and combined 0–30 cm depths.

		Jun 2017		May 2018		May 2019		Aug 2020		Changes in soil organic C in 39 months	Annual C gain
Treatment		0–15 (cm)	15–30 (cm)	0–15 (cm)	15–30 (cm)	0–15 (cm)	15–30 (cm)	0–15 (cm)	15–30 (cm)	0–30 (cm)	0–30 (cm)
Mg C ha^{-1}										(Mg C ha^{-1} 39 months^{-1})	(Mg C ha^{-1} year^{-1})
Control		3.81c	1.71ab	3.82bc	1.696b	3.91b	2.14ab	3.85b	1.95ab	0.62ab	0.156b
B+Com		4.23b	1.76ab	4.35a	1.68b	4.80a	2.28a	3.70b	1.65ab	0.17b	0.042c
Cover crop		3.68c	1.56b	3.50c	1.84ab	3.86b	1.85b	3.48b	1.46b	−0.23b	−0.058d
Cover crop/B+Com		4.86a	1.90a	3.94b	1.97a	4.73a	2.50a	4.52a	2.08a	1.42a	0.356a
SEM		0.066	0.072	0.096	0.061	0.147	0.116	0.188	0.151	0.315	0.080
Source of variation	df	*P* value									
B+Com	1	***	*	**	NS	***	*	*	NS	NS	
Cover crop	1	*	NS	***	*	NS	NS	NS	NS	NS	
B+Com × cover crop	1	***	NS	NS	NS	NS	NS	**	*	**	
Mg N ha^{-1}										Mg N ha^{-1} 39 months^{-1})	(Mg N ha^{-1} year^{-1})
Control		0.346b	0.149a	0.357a	0.173ab	0.377ab	0.204ab	0.370ab	0.211a	0.068ab	0.017a
B+Com		0.350b	0.144ab	0.353a	0.167b	0.391a	0.182bc	0.340b	0.176ab	0.031b	0.008d
Cover crop		0.315c	0.119b	0.316b	0.171ab	0.355b	0.164c	0.342b	0.159b	0.080ab	0.020b
Cover crop/B+Com		0.375a	0.164a	0.351a	0.190a	0.399a	0.214a	0.387a	0.209a	0.124a	0.031c
SEM		0.005	0.007	0.007	0.006	0.008	0.008	0.014	0.012	0.023	0.003
Source of variation	df	*P* value									
B+Com	1	***	*	*	NS	**	Ns	NS	NS	NS	
Cover crop	1	NS	NS	**	NS	NS	Ns	NS	NS	NS	
B+Com × cover crop	1	***	*	**	NS	NS	**	**	*	NS	

Note: Biochar compost applied to alleys and cover crop sowed in May 2017 and May 2019. df, degree of freedom; SEM, standard error mean; ***, **, *, significant at $P = 0.001$, 0.01, and 0.05, respectively; NS, non-significant at $P = 0.05$.
Means in the same column with the same letter were not significantly different ($P < 0.05$, Student's *t* test).

in cover crop/B+Com in the top 30 cm soil. The annual C sequestration rates were increased from 0.156 Mg ha^{-1} year $^{-1}$ in control to 0.356 Mg ha^{-1} year $^{-1}$ in cover crop/B+Com treatment. These values translate to the C retention values of 1.5%–2.9% in B+Com and 2.3%–8.8% in cover crop/B+Com assuming 25 Mg C ha^{-1} input by B+Com and 31.3 Mg C ha^{-1} input by cover crop/B+Com. Over the period of 39 months, soil total N in 0–30 cm soil depth was not affected by any of the treatments or their interactions. The average annual soil total N gain rate across the treatments was 0.019 Mg ha^{-1}.

Yield, fruit quality, pruning weights, and petiole N concentration

From the measured yield and fruit quality parameters in 2018, only the number of clusters and soluble solids were affected by treatments (Table 6). B+Com treatment resulted in the greater number of clusters relative to control and cover crop/B+Com in 2018. The number of clusters in cover crop treatment was not different from B+Com, control, or cover crop/B+Com. In 2018, greater soluble solids were measured in cover crop/B+Com and control compared with B+Com, but on par with cover crop. In 2019, the effects of treatments on measured parameters were not significant except for the effect of cover crop on cluster size, where larger average cluster weights were measured in cover-cropped treatment relative to non-cover cropped. Total yield was significantly greater in cover crop/B+Com than B+Com or CC (32% and 34% differences, respectively), but on par with control treatment in 2020. Cluster size was significantly greater in cover crop/B+Com than B+Com, but on par with cover crop and control treatments in 2020. Soluble solids were significantly greater in B+Com than control and cover crop/B+Com cover crop/B+Com, but on par with cover crop treatment in 2020. Pruning weights in 2020 were reduced by 29.4% in cover crop treatment relative to non-cover cropped treatments. Leaf petiole N concentrations in 2018 and 2020 were significantly affected by cover crop treatment (Table 6), where cover crop treatment reduced petiole N concentrations by 44.9% and 29.8%, respectively, compared with non-cover cropped treatment (0.49% vs. 0.71%; 0.57% vs. 0.74%). In 2019, leaf petiole N concentrations were not affected by the treatments.

Table 6. Mean values and ANVOA for the effect of alley biochar–compost (B+Com) and cover crop treatments on grape yield and fruit quality.

Treatment		Ave berry weight (g)	No. of clusters (plot^{-1})	Total yield (Mg ha^{-1})	Cluster size (kg)	Soluble solids (Brix)	Titratable acidity (g tartaric acid/100 mL juice)	Yeast assailable N (mg L^{-1})	Pruning weight (Mg ha^{-1})	Petiole N (%)
2018										
Control		1.55	46.5b	8.24	0.17	23.3a	1.13	226	2.33	0.71
B+Com		1.55	66.0a	11.1	0.16	22.5b	1.19	167	2.24	0.72
Cover crop		1.63	61.3ab	10.3	0.17	22.9ab	1.14	166	2.50	0.48
Cover crop/B+Com		1.58	46.5b	7.16	0.15	23.3a	1.10	192	2.44	0.50
SEM		0.053	5.64	1.49	0.014	0.32	0.031	33.1	0.14	0.06
Source of variation	df					*P* value				
B+Com	1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Cover crop	1	NS	NS	NS	NS	NS	NS	NS	NS	**
B+Com × cover crop	1	NS	*	NS	NS	*	NS	NS	NS	NS
2019										
Control		1.64	129	18.8	0.14	19.7	1.21	366	3.74	0.95
B+Com		1.70	135	21.2	0.16	19.5	1.13	261	3.94	0.72
Cover crop		1.68	125	21.1	0.17	19.8	1.14	272	4.18	0.76
Cover crop/B+Com		1.69	117	21.4	0.18	19.9	1.13	301	3.87	0.82
SEM		0.040	4.96	1.63	0.007	0.47	0.024	34.6	0.29	0.07
Source of variation	df					*P* value				
B+Com	1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Cover crop	1	NS	NS	NS	**	NS	NS	NS	NS	NS
B+Com × cover crop	1	*NS*	NS	NS	NS	NS	NS	NS	NS	NS
2020										
Control		1.42	97	4.91ab	0.081a	23.5b	1.06	241	3.40	0.72
B+Com		1.07	114	3.36b	0.047b	27.0a	1.06	223	2.65	0.76
Cover crop		1.24	107	3.71b	0.057ab	25.6ab	0.961	218	2.11	0.57
Cover crop/B+Com		1.36	116	5.50a	0.078a	23.3b	0.971	223	2.17	0.57
SEM		0.124	12.2	0.770	0.009	1.08	0.052	8.95	0.26	0.036
Source of variation	df					*P* value				
B+Com	1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Cover crop	1	NS	NS	NS	NS	NS	NS	NS	**	**
B+Com × cover crop	1	NS	NS	*	*	*	NS	NS	NS	NS

Note: df, degree of freedom; *, significant at $P < 0.05$; NS, not significant at $P < 0.10$; SEM, standard error mean.
Means in the same column with the same letter were not significantly different ($P < 0.10$, Student's *t* test).

Discussion

Cover crop biomass and C and N content

Our hypothesis that the addition of B+Com will increase cover crop biomass and consequently cover crop-driven C and N input to soil was rejected, because B+Com application did not change total dry biomass in the first 2 years and reduced it in the third year. The cover crop-driven C was not affected by B+Com application, while cover crop-driven N was affected and reduced only in the third year. Only few studies tested the effect of a biochar on cover crop biomass and cover crop-driven C and N content in vineyards of temperate regions. Our results were supported by Hüppi et al. (2016), who reported no significant effect of 20 Mg ha^{-1} wood chip biochar application on the yield of green rye (*Secale cereale* L.) cover crop or its biomass C and N content in a 2-year study at Reckenholz Zurich in sandy loam and silt loam soils. In another study, Verhoeven and Six (2014) observed a 155% increase in cover crop (a mixture of sweet pea (*Lathyrus odoratus* L.), vetch (*Vicia sativa* L.), faba bean (*Vicia faba* L.), and barley (*Hordeum vulgare* L.)) biomass with an application of 10 Mg ha^{-1} pine chip biochar in the first year, but no differences in biomass in the second year, and no differences in the biomass C and N content in both years in a commercial vineyard located in Sacramento County, USA, with sandy clay loam soil. The inconsistency in the reported biochar application effects on cover crop biomass or C and N contents between years can be attributed to existence of an un-pyrolyzed labile C fraction in the biochar that encourages the N mineralization after a short N immobilization phase in the year of application (Nelissen et al. 2015). Their results were different from ours likely due to differences in biochar feedstock, cover crop species, and soil type among other factors.

The effect of biochar on soil mineral N immobilization has been reported in several studies (Kolb et al. 2009; Novak et al. 2010), which can lead to negative effect on cover crop biomass and C or N content particularly in non-leguminous species. Bruun et al. (2012) showed that application of wheat straw biochar resulted in 43% increase in soil mineral N immobilization during 65 days of incubation at 23 °C. They corresponded this effect to existence of an un-pyrolyzed labile carbohydrate fraction in the biochar, which supported a larger microbial biomass C compared with control. Nelissen et al. (2015) also reported a considerable immobilization of nitrate and ammonium after application of a 20 Mg ha^{-1} wood-based biochar in a field experiment in Belgium. The N immobilization after biochar application is temporary as the labile biochar C will be mineralized after a few months (Nelissen et al. 2015). Biochar can also accelerate soil micro-organism processes and further soil N immobilization through a change in soil pH, microbial protection in biochar pores, bacterial adhesion or sorption of compounds that would otherwise inhibit microbial growth (Lehmann et al. 2011). For N fixing species (i.e., legumes) soil available N is not a growth-limiting factor, while in grasses (the dominant species in our study) and cereals (Hüppi et al. 2016) soil available N is a critical factor for their biomass production (Verhoeven and Six 2014). The lack of cover crop biomass response to biochar application in 2017 may relate to carryover of mineral N from a previous season, and in 2018 to the diminished immobilization capacity of the biochar after a year of aging in the field. The reduction in cover crop biomass and N content in 2019 can be associated with a fresh application of biochar with a high N immobilization capacity plus limited carryover of the mineral N from the previous year (Nelissen et al. 2015).

Soil C and N content

Biochar average C and N concentrations were lower in C (78%–79%), but within the range reported for N (0.4%–0.9%) compared with data reported by Baronti et al. (2014) and García-Jaramillo et al. (2021). The hypothesis that addition of B+Com or planting cover crop in the vineyard's alleys will increase soil organic C in 0–30 cm soil depth was partially accepted for B+Com, but rejected for cover crop. The positive effect of B+Com on soil organic C was only in 0–15 cm soil depth. Few studies have evaluated the effect of biochar application on soil C and N in vineyard's alleys (Baronti et al. 2014; García-Jaramillo et al. 2021), and only 1 study evaluated the effect of B+Com on soil organic C (Niehues 2015). Our findings were supported by García-Jaramillo et al. (2021), who tested the effect of 18 and 35 Mg ha^{-1} undervine application of a wood-based biochar on soil organic C and total N 6 months after application in 2 pinot Noir vineyards with loam to clay loam soil texture in Oregon, USA. They reported a 60% to >100% increase in soil total C in both application rates and in both locations compared with unamended control. The high magnitude of biochar effect on soil total C in García-Jaramillo et al. (2021) can be associated with 34% greater C concentration in their biochar compared with our study and their high rate of biochar application that was more than twice as high as our rate (11 Mg ha^{-1}). Baronti et al. (2014) did not report any data on the soil C. Niehues (2015) reported greater net C sequestration with application of B+Com compared with other organic fertilization practices in Napa Valley, USA, vineyard soils.

Several studies on other crops particularly on field crops (e.g., wheat, corn, and ryegrass) reported a significant increase in soil C as a result of biochar application (Weng et al. 2017; Shi et al. 2021). Shi et al. (2021) observed 16%–82% increase in soil organic C content by 10 years annual application of 4.5 and 9.0 Mg ha^{-1} corn cobs biochar in winter wheat–corn rotation in a silt loam soil in Shandong Province, China. In their study, biochar C was mainly allocated to particulate organic C fraction (38%–166%). They attributed the greater soil organic C accumulation in biochar treatment compared with control to high C content of biochar, as well as its potential negative priming effect on the native soil C (Shi et al. 2021). Also, aromatic structure of C in the biochar resists the microbial degradation (Zhao et al. 2020). The negative priming effect of biochar may occur through 2 main mechanisms: enhanced formation of soil aggregates by improving organo-mineral interactions, therefore an increase in physical protection of soil organic matter (Maestrini et al. 2015; Weng et al. 2017), and adsorbing and stabilization of dissolved organic C or acid root exudates (Whitman et al. 2014). As the input of biochar C was through the soil surface in our study, the main accumulation of the C was found in 0–15 soil depth. Similarly, Weng et al. (2017) in a subtropical annual ryegrass field system found an increase of 13.3 Mg C ha^{-1} in the total soil organic C stock (0–10 cm soil depth) 8.2 years after the incorporation of a 10 Mg ha^{-1} eucalyptus biochar ($C = 76\%$). The positive effect of biochar application on soil inorganic C was reported by Shi et al. (2021); however, soil inorganic C was not evaluated in our study.

Cover crops with the goal of C sequestration have been increasingly used in the vineyards. Although we did not find any significant effect of cover crop treatment on soil C content, Poeplau and Don (2015) reported an annual soil organic C stock change rate of 0.32 ± 0.08 Mg ha^{-1} year $^{-1}$ in top 22 cm soil and during the observed period of up to 54 years when compiling the data from 139 cover crop plots at 37 different sites. However, they also noticed a reduction in soil organic C stock in 13 out of 139 plots after introducing cover crops. The lack of effect or reduction in soil organic C with cover cropping practice can be associated with (*i*) addition of rapidly decomposable plant material (low C/N ratio) that leads to enhanced microbial community activity, therefore fast turnover of newly added organic matter and positive priming effect on native soil organic C, and (*ii*) the high spatial variability of soil organic C concentrations in the soil that masks the small effects of cover crops on soil organic C (Poeplau and Don 2015). The former effect will be magnified when physical protection by soil particles is minimal, i.e., light-textured soils, which was the case in our study (Maestrini et al. 2015). The masking effect of spatial variability becomes more likely, when the time since establishment of cover crop treatment is not long (e.g., <7 years) (Poeplau and Don 2015). Goidts et al. (2009) found that only soil organic C concentrations changes >20% could be detected in the field. The C/N ratio of cover crop residues is also an important indicator of their turnover time in the soil (Schimel and Weintraub 2003). In our study, we only measured the soil organic C content at the top 30 cm soil depth, which might not fully capture the total effect of deep rooting cover crops on soil organic C stock. Also, we did not measure cover crop belowground C contribution; therefore, the input of C was likely underestimated. Gattullo et al. (2020) carried out a 3-year study with a fescue (*Festuca arundinacea* Schreb.) cover crop in a table grape vineyard in southern Italy on a silt loam soil and reported the average increase of 136% of soil organic C content in the cover crop treatment (0–20 cm soil depth) compared with control. The positive soil organic C response to cover crop in their study can be attributed to higher root/shoot ratio of grass, lower C/N ratio of residues, heavier soil texture, and lower initial organic C content of the soil (2.6 g kg^{-1}) compared with our study (Gattullo et al. 2020).

The hypothesis that addition of B+Com or sowing cover crop in the vineyard's alleys will increase soil total N in 0–30 cm soil depth was rejected, as B+Com did not affect and cover crop reduced soil total N in 0–30 cm soil depth. García-Jaramillo et al. (2021) reported an increase in soil total N only in 1 of the 2 studied vineyards with 35 Mg ha^{-1} undervine application of a wood-based biochar in Oregon, USA. Biochar is not considered as a source of N in literature due to its low concentration of N (Baronti et al. 2014; García-Jaramillo et al. 2021). Cover crops, however, are reported as the main input of N to the soil. Tarricone et al. (2020) reported an average of 18% increase in soil total N using subterranean clover (*Trifolium subterraneum* L.) or vetch as undervine cover crop in a table grape vineyard in Italy. The reduction in soil N in 0–30 cm depth in our study can be related to low N input using a grass-based cover crop (Tarricone et al. 2020), light texture of the soil with low physical protection capacity (Maestrini et al. 2015), possibility of N leaching, and high spatial variability in soil total N concentration (Poeplau and Don 2015).

The hypothesis on the positive interaction of B+Com and cover crop on soil organic C and total N in 0–30 cm soil depth was accepted only for 0–15 cm depth. We observed a positive effect of B+Com on cover crop-derived C accumulation. The cover crop-derived C consists of aboveground and belowground residues and root exudates. Weng et al. (2017) found 20% greater belowground recovery of new root-derived C by field-aged biochar, which corresponded to facilitation of negative rhizosphere priming. Other studies reported 16%–48% reduction in soil organic C mineralization rate when incorporating plant residues in a soil that received biochar application (Whitman et al. 2014; Keith et al. 2015; Weng et al. 2015). Weng et al. (2017) measured higher recovery of the new root-derived C in a biochar-amended soil and suggested that biochar may have promoted the root exudation and consequently soil aggregation process. The greater protection of root-derived particulate organic matter C or exudates in biochar-amended soil associates with 2 mechanisms of physical occlusion or organo-mineral interactions (Joseph et al. 2020). Our results were also supported by Messiga et al. (2015), who reported 9%–11% greater soil organic C concentration and 8%–10% soil organic N in a combination of cover crop and an soil amendment treatment compared with amendment or cover crop alone in a 2-year study in a vineyard in Nova Scotia, Canada.

Yield, fruit quality, pruning weights, and petiole N concentration

The hypothesis that B+Com or cover crop or their combination in the vineyard's alleys will positively affect vine growth, grape yield, fruit quality, and vine N status was rejected except for the positive effect of cover crop/B+Com on yield in 2020. The effect of B+Com on increasing the number of clusters and reducing berry soluble solids in 2018 was aligned with a trend towards higher yield values in this treatment (Sivilotti et al. 2020; Bates et al. 2021). The mechanism of this effect is not clear, but could be due to a more balanced vine vigour due to immobilization of soil N in this inherently vigorous vineyard (Bruun et al. 2012; Zhang et al. 2012; Nelissen et al. 2015). In 2019, the average cluster size was increased by cover crop treatment, but the reason for this change is not clear. The lower yield in B+Com or cover crop treatments compared with cover crop/B+Com treatments in 2020 can be attributed to N immobilization by B+Com or competition for N between cover crop and vine (Bruun et al. 2012; Zhang et al. 2012; Nelissen et al. 2015). The effect of fresh application of B+Com on soil N immobilization was confirmed by small average cluster size and greater soluble solids compared with other treatments in 2020. The reverse relationship between yield and soluble solids was reported in several studies and was associated with the dilution of photosynthates (Sivilotti et al. 2020; Bates et al. 2021). The reduction in pruning weight in 2020, and petiole N concentration in 2018 and 2020 by cover crop treatment can be related to competition for resources between cover crop and vine. Petiole N usually exhibits a significant and positive correlation with available N in the depth of 0–30 cm (Bhat et al. 2017).

Grape yields and fruit quality parameters were within normal ranges typically observed for Merlot in the Okanagan Valley, BC, Canada (Neilsen et al. 2010; Hannam et al. 2016*a*), except for titratable acidity that was on the high end. The lack of B+Com treatment effect on yield and majority of fruit quality parameters in 2018 and 2019 was supported by García-Jaramillo et al. (2021), who reported no yield or berry chemistry significant responses to biochar application treatments in Oregon, USA. In contrast, Genesio et al. (2015) reported a significant increase in grape yield after the first year of biochar application at 22 Mg ha^{-1}. Their vineyards were under moderate to severe water deficits as discussed by

Baronti et al. (2014). In the Baronti et al. (2014) study, soil water holding capacity and vine water status were improved by biochar application; therefore, the observed increased yield by Genesio et al. (2015) can be associated with improved vine water status. In our study, the vineyard was irrigated during the summer and therefore no soil water deficit was expected, and consequently no response of yield to B+Com application was observed. The lack of fruit quality parameter response to biochar application is also reported by Schmidt et al. (2014) and Genesio et al. (2015). It has been reported that vine yield and physiological response to biochar application is more likely to be seen under water deficit conditions; therefore, more studies on interactions of biochar and soil water status in Okanagan Valley region can be recommended.

The slight or no effect of cover crop treatments on grape yield and fruit quality is common and was reported in several studies (Giese et al. 2014; Sharifi et al. 2018; Tarricone et al. 2020). Gattullo et al. (2020) reported no effect of cover crops on yield or fruit quality except for 1 out of 3-year yield reduction that was associated with low precipitation in the growing season in that year. The low precipitation in the summer can trigger the competition for water between vine and cover crop, consequently leading to reduced vine vigour and yield. Reductions in grape yield as a result of cover crop practice were reported in a number of studies, which were mainly attributed to competition for the resources (Morlat and Jacquet 2003; Muscas et al. 2017). The competition for water and nutrients under cover crops and immobilization of nutrients by biochar can lead to reduction in the vegetative and reproductive growth of vigorous vines, therefore improving cluster exposure to light and air, reducing pest and diseases, and improving fruit composition. In our study, the reduction in pruning weight and petiole N, and consequently, enhanced soluble solids, was evident in some years. Messiga et al. (2016) reported an increase in the second year grape yield when a combination of soil amendment and cover crop was used in an infertile soil in southern Nova Scotia, Canada. They reported the greatest yield in oats and red clover (*Trifolium pretense* L.) mixture combined with muscle sediments (9.52 Mg ha^{-1}) followed by oats, pea, and vetch mixture combined with municipal solid food waste compost (9.49 Mg ha^{-1}). Their highest berry sugar concentrations among the cover crops were obtained under timothy grass (*Phleum pratense* L.) cover crop and attributed to elevated competition between vine and grass for nutrients compared with control.

Conclusion

The effects of B+Com or cover crop or their combination were assessed on soil C and N, and grapevine productivity in an irrigated Merlot vineyard in Okanagan Valley, BC, Canada. We hypothesized that B+Com application in the vineyard's alleys has a positive effect on cover crop biomass and consequently cover crop-driven C and N input to the soil will be increased. This hypothesis was rejected and the lack of cover crop response to B+Com was associated with increased soil N immobilization due to existence of an un-pyrolyzed labile carbohydrate fraction in the biochar that supports a larger microbial biomass compared with control. The hypothesis that B+Com or cover crop or their combination will increase soil organic C and total N was accepted for B+Com-derived C, but rejected for B+Com-derived N and cover crop derived-C and N. The positive effect of B+Com on soil organic C was attributed to high C content of biochar, as well as its potential negative priming effect on the native soil C. The input of N through B+Com was limited and therefore no effect on soil total N was observed. The lack of response to cover crop likely connected to fast turnover of cover crop-driven C and N, positive priming effect of cover crop on soil native organic C and N, and high spatial variability of these parameters in the field. The hypothesis that treatments will positively affect vine growth, grape yield, fruit quality, and vine N status was rejected except for the positive effect of cover crop/B+Com on yield in 2012. This lack of yield and fruit quality response to B+Com and cover crop can be attributed to N immobilization by B+Com or competition for N between cover crop and vine. The positive interactive effect of B+Com and cover crop was likely associated with the preservation and protection of cover crop-derived C and N by B+Com. In semi-arid light-textured vineyard soils, the use of B+Com in combination with a high C/N ratio cover crop can be recommended to increase C and N residence time and consequently enhance C sequestration rate in the soil. Under the conditions of this study, use of cover crops alone in the vineyard's alleys might not be efficient for storing C and N in the soil in short term. The effect of biochar on soil inorganic C was not evaluated in this study, but was observed in other studies and requires investigation. Future studies are required to unveil the longer term effects and to explore effects of B+Com or cover crop or their combination on alleys' soil compaction and soil water holding capacity, which are industry-wide issues in semi-arid Okanagan Valley, BC, Canada.

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Data generated or analyzed during this study are provided in full within the published article.

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Mehdi Sharifi: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review & editing; Monireh Hajiaghaei Kamrani: formal analysis, visualization, writing – review & editing.

Competing interests

The authors declare that there are no competing interests.

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