Agriculture, Ecosystems and Environment xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality

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ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 23 March 2014
Accepted 1 April 2014
Available online xxx

Keywords:
Vineyard
Biochar
Composting
Biochar-compost
Fruit quality
Plant health

ABSTRACT

Most European vineyard soils exhibit low soil fertility. They are highly vulnerable to erosion, low in soil organic matter content and, therefore, in water holding capacity and nitrate retention. The applications of biochar and biochar-compost are said to address some of these issues. We tested the ability of these amendments to improve soil quality and plant production quality in a 30-year-old vineyard in Valais, Switzerland. The amendments of biochar alone (8 t ha^{-1}, produced from wood at 500 °C), aerobic compost (55 t ha^{-1}) and biochar-compost (8 t ha^{-1} + 55 t ha^{-1}, mixed before the composting process) were compared to an un-amended control soil. During the years 2011, 2012 and 2013 various vine and green cover growth, vine health and grape quality parameters were monitored. Biochar and biochar-compost treatments induced only small, economically irrelevant and mostly non-significant effects over the three years. We concluded that topsoil application of higher amounts of biochar has no immediate economic value for vine growing in poor fertility, alkaline, temperate soil.

1. Introduction

Historically, most European vineyard soils exhibit low soil fertility. They have low soil organic matter content, low water holding capacity and often, due to compaction, poor soil aeration (Casalí et al., 2009; Martı′nez-Casasnovas and Sánchez-Bosch, 2000; Tropeano, 1984). While vineyards are often subjected to severe water stress during hot, dry summers, optimal water supply for the vines is one of the major criteria for wine quality (Bravdo et al., 1985; Jackson and Lombard, 1993). It is expected that periods of drought will become longer and more severe in most of European wine growing regions (Schultz, 2000) in particular with on-going global warming. Drought may alternate with strong rain events which are both equally detrimental to wine quality (Jones et al., 2005). Excessive precipitation during critical phases of vegetative vine development (especially between fruit setting and grape closing as well as between veraison and harvest) often results in increased fungal pathogen pressure and excess nutrient mineralisation leading to an imbalance in vegetative versus reproductive growth of grapevines, thereby decreasing fruit quality variables (Schreiner et al., 2013; Wheeler and Pickering, 2003).

The addition of biochar to soil has recently been proposed as a way to improve soil water holding capacity (Busch et al., 2012; Busscher et al., 2010; Kammann et al., 2012; Karhu et al., 2011), water infiltration (Asai et al., 2009; Ippolito et al., 2012), soil water availibility (Baronti et al., 2014), nutrient retention (Clough et al., 2013; Ventura et al., 2013), hydraulic conductivity (Buss et al., 2012), and soil aeration (Case et al., 2012; Cayuela et al., 2013). Thus, the addition of biochar to vineyard soils can, in theory, improve vine growth and especially fruit quality, as combinations of aromas, flavours, tannins, sugars, and acids create the unique varietal character of wine grapes. Other suggested effects of biochar, such as increased microbial activity (Lehmann et al., 2011; Warnock et al., 2007), shifts in microbial diversity (Jin, 2010), increase in electrical conductivity (Husson, 2012) and immobilisation of contaminants such as trace elements (especially Cu) (Borchard et al., 2012; Buss et al., 2012; Ippolito et al., 2012) or pesticides (Gomez-Eyles et al.,

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http://dx.doi.org/10.1016/j.agee.2014.04.001
0167-8809/

2013; Graber et al., 2012) could also have an influence on vines. However, significant increases in soil fertility, plant growth and yield have mostly been reported when biochar was applied to tropical and subtropical soils (Asai et al., 2009; Atkinson et al., 2010; Glaser et al., 2002; Lehmann and Rondon, 2006; Lehmann and Steiner, 2009; Major et al., 2010b). Only a few results exist from larger field trials with perennial crops grown in temperate soils (Ventura et al., 2013), including only one biochar field trial in vineyards (Baronti et al., 2014). Two meta-analyses (Biederman and Harpole, 2013; Jeffery et al., 2011) suggest that in temperate climate, the effect of biochar is less pronounced. However, the trials investigated in both meta-analyses did not include composted or otherwise nutrient-enriched biochar and compared solely the effect of freshly produced biochar to the respective control.

It has recently been demonstrated that the use of freshly produced biochar may lead to reduced plant growth due to nutrient immobilisation caused especially by the adsorption of mineral nitrogen (N_{min}) and dissolved organic carbon (DOC) (Ding et al., 2010; Graber and Elad, 2013; Jin, 2010; Taghizadeh-Toosi et al., 2011). In order to eliminate or offset negative effects of freshly produced biochar, it was suggested to enhance the biochar with organic or mineral nutrients (Alburquerque et al., 2012; Bruun et al., 2011; Gathorne-Hardy et al., 2009; Joseph et al., 2013a,c). Especially blending with compost or the co-composting of biochar (Fischer and Glaser, 2012; Steiner et al., 2010) was proposed to charge the porous biochar matrix and adsorptive surfaces with nutrients, stimulate microbial colonisation (Pietikäinen et al., 2003), degrade possible noxious pyrogenic substances (Tuomela et al., 2000), and improve the biochar surface reactivity through accelerated oxidative ageing (Cheng and Lehmann, 2009; Zimmerman, 2010) as well as DOC adsorption (Prost et al., 2012). Thus, in the present study, we included a biochar-compost (bc-compost) treatment, which was compared to freshly produced biochar (bc) and to non-biochar-amended compost (compost).

Unlike most other field crops, the economic success of viticulture depends more on fruit quality rather than on yield. Several standard parameters of grape quality are widely used in viticulture allowing comparison of quality between vintages and regions. Sugars, polyphenol, anthocyanins, and assimilable N content in grapes (Downey et al., 2006; Reeve et al., 2005) combined with acidity and the reduction capacity of the grape provide a sophisticated estimation of the grape quality (Abbott, 1999; Cagnasso et al., 2008; Saint-Cricq et al., 1998). However, so far no studies have considered the effect of biochar on these intrinsic qualities of the agricultural product.

In 2011, a field trial was established on vineyard plot in Valais, Switzerland, planted with Pinot noir vines, where three soil amendments were compared: biochar, aerobic compost and biochar-compost (biochar was added before the composting process). Over the three subsequent growing seasons (2011–2013), we investigated the following hypotheses: (1) biochar applications will show positive agronomic effects on low-fertility calcareous soils in a temperate climate, (2) biochar-compost substrate will at least in the first years have better effects on vine growth compared to fresh biochar and also compared to compost alone, and (3) biochar and biochar-compost substrates will have positive effects on grape quality and the sensitivity of the vines to two main fungal pathogens.

2. Materials and methods

2.1. Experimental site

The field site of 960 m^2 was located in Ayent, Valais, Switzerland (46°26′88.94 N/7°40′78.21 W) on the southern face of the Rhone valley at an altitude of 820 m. The mean temperature, annual precipitation and annual global radiation at the nearby meteorological station of Venthone were 11.6 °C, 496 mm and 1335 kWh m^{-2} in 2011, 10.7 °C, 614 mm and 1288 kWh m^{-2} in 2012, and 10.4 °C, 568 mm and 1245 kWh m^{-2} in 2013, respectively. The soil has been classified as a Haplic Regosol (WRB) with 47% skeleton, 26% clay, 32% silt, and 42% sand in the <2 mm soil fraction. Further soil analytical parameters are summarised in Appendix Table 1.

The experiment was set up in a field where grape vines (variety *Vitis vinifera* cv. Pinot Noir) were planted 25–35 years ago. The plot was cultivated conventionally until 2010 and then cultivated as organic viticulture i.e. excluding mineral fertilisation and chemical pesticide use. A green cover was sown following the trial set-up in spring 2011. The green cover was composed of 50% *Lotus corniculatus*, 22% *Medicago lupulina*, 25.4% *Trifolium* spp., 2% *Anthyllis vulneraria*, 0.1% *Hippocrepis comosa*, and 0.5% mix of various herbs. Apart from this leguminous N-fixing cover, no fertilisation was applied to the grape vines. Between the end of May and the beginning of August, six phyto-sanitary treatments (S, $Cu(OH)_2$, $CuSO_4$) were applied, amounting to application rates per hectare of 16 kg S and 2 kg Cu in 2011, 16 kg S and 400 g Cu in 2012, and 8 kg S and 350 g Cu in 2013, respectively.

2.2. Experimental setup

The field trial was set up with 5 blocks along the slope gradient each containing a control and three substrate treatments (see Appendix Fig. A1). Each plot included four grape vine rows and three inter-rows, respectively. The three substrate treatments were: biochar alone (referred to hereafter as 'biochar'), compost alone ('compost') and compost produced together with initially 20 vol% biochar, i.e. the biochar was already present during the composting process ('bc-compost'). The applied quantities were determined on the basis of 30 m^3 biochar ha^{-1} which was equivalent to 8 t ha^{-1} (dry mass, corresponding to 10 t production fresh weight biochar which is a common amount for biochar field trials (Biederman and Harpole, 2013; Jeffery et al., 2011)). Based on the assumption that biochar represented 30% (vol) of the bc-compost mix, 102 m^3 ha^{-1} (63 t ha^{-1}) of bc-compost and 72 m^3 ha^{-1} (55 t ha^{-1}) of pure compost were applied in the 'bc-compost' and 'compost' plots, respectively. All substrates were applied on June 8th, 2011 at the beginning of the main growth period of the vines. After the spreading of the different substrates by hand onto the soil surface (vine rows included), the soil was superficially tilled in the inter-rows with a tiller to 7–10 cm depth. One day after application and tillage, the green cover mix was sown on the entire surface (vine rows included) by hand (1.5 g m^{-2}). The seeds germinated 10 days later.

2.3. Biochar and compost characterisation

The biochar was produced from 80% varied hardwood and 20% varied coniferous wood chips. Pyrolysis took place in a "Schottdorf"-type reactor (Carbon Terra GmbH, Augsburg, Germany) at 750 °C in a 36 h cycle. The biochar had a pH of 9.5, a carbon content of 76% and H/C_{org} molar ratio of 0.2. Its specific surface (BET) area was 144 m^2 g^{-1}. All analytical parameters were well within the thresholds of the European Biochar Certificate (EBC, 2012). Further physical and chemical properties of the biochar used in this trial are summarised in Appendix Table 2. The compost was produced following a standard protocol for professional aerobic quality composting (Kompostforum-Schweiz, 1998). The piles were turned each day for the first five weeks and watered when necessary (daily water content determination). For the following three weeks, the piles were turned every three days. After eight weeks, when the pile core temperatures approached ambient temperatures the piles were assembled and transported to the field site. Before the application, substrates were tested for ecotoxicology using a closed cress test (Fuchs, 2000) showing no effects of plant growth inhibition. The main characteristics of the ripe compost and bc-compost substrate are summarised in Appendix Table 3.

2.4. Plant sampling and analysis

2.4.1. Plant biomass and fertility

The effect of the organic inputs on plant performance was evaluated on the vines (shoot diameter, flower to shoot ratio) and leaves (mineral N content, micro-element analysis, plant health), 4, 16 and 28 months following the application of the organic amendments. Plant material was always sampled in the middle rows of the grape vine lines of each plot to avoid edge effects. The shoot diameter was measured at the first shoot of each vine in the middle of the third internode, counted from the bottom. The total number of flowers and of new primary shoots of the respective year were counted on each plant and expressed as the flower to shoot ratio in order to evaluate changes in the fertility of the grape vines.

Thirty leaves per plot were measured for mineral N foliar analysis (non-destructive) using a Yara N-tester (Yara International ASA, Norway) at the phenological stage of veraison (beginning of berry ripening). Optimal reference values for grape vines, cv. Pinot noir, are in the range of 500–550 on the Yara scale (Spring et al., 2003).

The second grape of the last tenons and the juxtaposing leaves were examined for symptoms of the pathogens *Plasmopara viticola* and *Oidium tuckerii* (12 plants per plot). The intensity of infection was classified according to the VITIVAL-scale (Vitival, 2010) from 1 to 8 for *Plasmopara* on berries, and from 1 to 6 for *Oidium* on berries and for both pathogens on leaves.

At the days of harvests on October 3rd, 2011 and October 15th, 2012 and October 21st, 2013, respectively, 1000 mL of berries were sampled from each plot from all grapes of all grape vines of both inner rows. The berries were pressed and the juice was collected in order to measure pH and must density in °Oechsle with a refractometer PCE-5890. On the harvest day in 2011, 60 berries per plot were sampled (five per vine tree, one per cluster). Five samples were pooled into a sample of 300 berries per treatment and sent in a cooler to LCA-Laboratoires La Rochelle. Total phenols and anthocyans were determined by high performance liquid chromatography with UV detection (Garciafalcon et al., 2007); total acidity, NH_4^+ Amino-N and yeast-assimilable N (NOPA) were determined by Fourier transform infrared spectroscopy (Urbano Cuadrado et al., 2005). On the harvest day in 2011, 180 berries per plot were sampled (five per grape cluster, three clusters per vine tree) and sent in a cooler to Weinlabor Kiefer in Maikammer, Germany. All grape parameter were determined by Fourier transform infrared spectroscopy with a Grapescan FT120 (Foss®).

2.5. Statistical analysis

Normality was tested with the Shapiro–Wilk-test and homogeneity of variances with Levene's test. When applicable, the significance between treatments was tested with an ANOVA ($p < 0.05$) for the data set following a normal distribution and with a Kruskal–Wallis test when the distribution was not normal. In the case of samples pooled per treatment from the different blocks, descriptive statistics was used.

3. Results

3.1. Grapevine growth (shoot growth, fertility, leaf nitrogen index)

We found no significant difference in shoot diameter between treatments, either in 2011, 2012 or 2013 (Table 1.) but a tendency in 2013 where shoot diameter in the bc-compost treatment was higher by 10% ($p = 0.218$) compared to the control and also higher than in the other treatments. In June 2012, twelve months after substrate application, grapevines treated with bc-compost produced significantly ($p < 0.05$) more flowers per shoot, while for the other two substrates no significant differences were found (Table 1). As grapevine fertility is mostly determined in the preceding growing season, the substrate application could not have had an influence on the flower production in the 2011 season and it was therefore only observed in 2012 and 2013. In June 2013, however, fertility did not differ significantly between the treatments. Compared to the control and the biochar treatment, a significant ($p < 0.05$) increase in the leaf Yara-N index was found in the compost treatment 4 months after the start (Table 1) though there was no significant difference between compost and bc-compost. In 2012 and 2013, however, no significant difference in the leaf-N index was observed. In 2012 and 2013 the leaf nitrogen index was lower in all treatments compared to 2011, likely due to an overall lower average temperature and increasing nutrient competition between the vines and the developing green cover.

3.2. Grapevine health

The overall infection rates in 2012 were low to medium on leaves and grapes for *P. viticola* and for *O. tuckerii*, although sufficiently high in order to identify effects of treatments. The only significant difference that occurred was found between bc-compost and compost for *Plasmopara* infections on leaves, with lower infections in the bc-compost treatment (Fig. 1). For all other investigated parameters no significant differences due to the treatments were observed (Fig. 1).

3.3. Grape and must quality

In 2011, four months after the start of the trial, the pH of grape must was significantly ($p < 0.05$) increased in all substrate treatments compared to the control, and in the bc-compost treatment compared to the biochar treatment (Table 2). In 2013, the pH did not differ significantly between the treatments whereas for 2012 the measures could not be included due to a mistreatment of the samples. Substrate treatments did not significantly influence the sugar content in all three years (Table 2). In all treatments, the sugar content was lower by nearly 4° Oechsle in 2012 compared to 2011 and 2013 due to lower average temperatures during the growing season (Table 2).

Additional grape quality parameters like tartric, malic, gluconic, volatile and total acids, glycerin, glucose to fructose ratio, NOPA or ammonium were determined in 2013. None of these parameters showed any significant difference between the treatments (due to the high cost of these analyses they were only done in the last year of the experiment). In 2011, however, grape quality parameter analyses were made on pooled samples indicating some differences especially for yeast assimilable nitrogen in the compost treatments (see Appendix Table A3).

4. Discussion

4.1. Treatment effects on vine growth in calcareous temperate soil

The vineyard biochar field trial was carried out on a calcareous soil that had been fertilised annually with >50 kg N ha^{-1} and regularly treated with herbicides before it was transferred to organic farming and green cover with the onset of this study. Resumed over the three years of the experiment, the study revealed no major significant effects of biochar, biochar-compost or compost on plant growth, nutrient uptake and plant health when compared to the control. Only in the first two years, some minor though rarely significant effects of biochar were observed indicating that non-composted biochar may have some negative effects on plant growth which level out over time. However, as the stem diameter was (non-significantly) higher by 10% in the bc-compost compared to the control (Table 1), a slow increase in plant growth parameters might be seen in the coming years.

A specific aspect of our set up may explain that only little changes were observed in this study. The vineyard consisted of 30-year-old vines, which usually have very deep-reaching roots, likely down to more than 3 m depth. As the substrates were incorporated into the first centimetres of the vineyard soil, more pronounced effects may be seen in the upcoming years, when the finer particles of the amendments will likely move down into deeper soil horizons as observed by Major et al. (2010a). It might further be that the conversion from conventional to organic farming and the installation of legume based green cover at the beginning of the trial

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Table 1
Grapevine growth analysis: effects of substrates on vegetative grapevine growth measured by the diameter in mm of primary one-year shoots in 2011, 2012 and 2013. Effects of substrates on grapevine nitrogen uptake in 2011, 2012 and 2013 measured by photospectrometry in 30 leaves per plot with Yara N-Tester. Effects of substrates on grapevine fertility measured in grapes per shoot in 2012 and 2013. Within rows, numbers represent the mean ± SE ($n = 5$). The treatments with different letters denote significantly difference at $p < 0.05$.

	Year	Control	Biochar	Compost	Biochar-compost
Shoot diameter in mm	2011	6.78 ± 0.15a	6.91 ± 0.41a	6.84 ± 0.41a	7.22 ± 0.23a
	2012	6.09 ± 0.68a	6.11 ± 0.38a	6.31 ± 0.45a	6.07 ± 0.79a
	2013	6.85 ± 0.22a	7.04 ± 0.44a	7.02 ± 0.46a	7.48 ± 0.65a
Leave nitrogen	2011	424 ± 43.4a	416 ± 33.8a	459 ± 38.2b	442 ± 57.4ab
	2012	398 ± 44.3a	405 ± 28.6a	430 ± 27.5a	406 ± 40a
	2013	391 ± 35a	409 ± 35.5a	425 ± 26.8a	417 ± 25.2a
Fertility in number of flowers per shoot	2012	1.55 ± 0.11a	1.4 ± 0.2a	1.58 ± 0.19ab	1.68 ± 0.13b
	2013	1.23 ± 0.26a	1.4 ± 0.16a	1.35 ± 0.08a	1.32 ± 0.14a

Table 2
Grape most analysis: effects of substrates on sugar content (in °Oe) and pH of the grape must. Numbers represent the mean ± SE ($n = 5$). Values with different letters are significantly different (at $p < 0.05$) in same line.

	Year	Control	Biochar	Compost	Bc-compost
Must weight in °Oechsle	2011	94.6 ± 4.33a	97.2 ± 2.68a	97.0 ± 4.12a	98.4 ± 3.91a
	2012	88.2 ± 4.43a	85.8 ± 3.63a	89.0 ± 4.3a	86.4 ± 3.36a
	2013	95.9 ± 2.02a	94.7 ± 1.11a	94.9 ± 1.33a	95.7 ± 1.44a
pH	2011	3.17 ± 0.045a	3.24 ± 0.024b	3.26 ± 0.051bc	3.28 ± 0.011c
	2013	3.41 ± 0.03a	3.38 ± 0.04a	3.41 ± 0.04a	3.42 ± 0.03a

had overall a more pronounced effect than the application of the biochar and/or compost amendments, thus hiding intrinsic effects of the treatments. However, the plant growth results are not in discordance to outcomes of some other biochar field trials in alkaline soils of temperate climates where only few positive effects on plant growth were observed (Atkinson et al., 2010; Biederman and Harpole, 2013).

4.2. Biochar versus biochar-compost additions

In the first two years the compost and bc-compost treatments caused small yet rarely significant improvements on plant growth, grape fertility and quality parameters compared to the biochar-only treatment and to the control. However, in the third year none of these parameters has shown any significant difference. Although the amount of N added with the compost and bc-compost was equal to an application of 514 kg N_{tot} ha^{-1} and 566 kg N_{tot} ha^{-1}, respectively (though only about 10–20% of the total N can be considered to be bioavailable during the first three growing seasons (Muñoz et al., 2008), corresponding to the yearly nitrogen demand of the vines), the effect on plant growth was lower than expected compared to the control. The lack of a clear effect on growth parameters in both, the compost and bc-compost treatments, compared to the control indicates that vine growth was likely not limited by nutrient availability (see also Appendix Table 1 for the soil analysis).

A significant negative effect of the biochar treatment compared to the bc-compost treatment was observed for grape fertility in 2012, and for Yara leaf N in the first year. Freshly produced biochar caused further negative, though mostly insignificant, tendencies in all plant-growth and leaf nutrient parameters in 2011 and 2012. These negative trends of non-composted biochar were positively reversed in the bc-compost and compost amendments, confirming results by a growing number of studies showing the importance to co-composted biochar compared to the application of production-fresh biochar (Fischer and Glaser, 2012; Glaser and Birk, 2012; Hua et al., 2012; Joseph et al., 2013b; Prost et al., 2012; Wang et al., 2013). However, negative effects of the fresh biochar became less pronounced in the second year and insignificant in the third year.

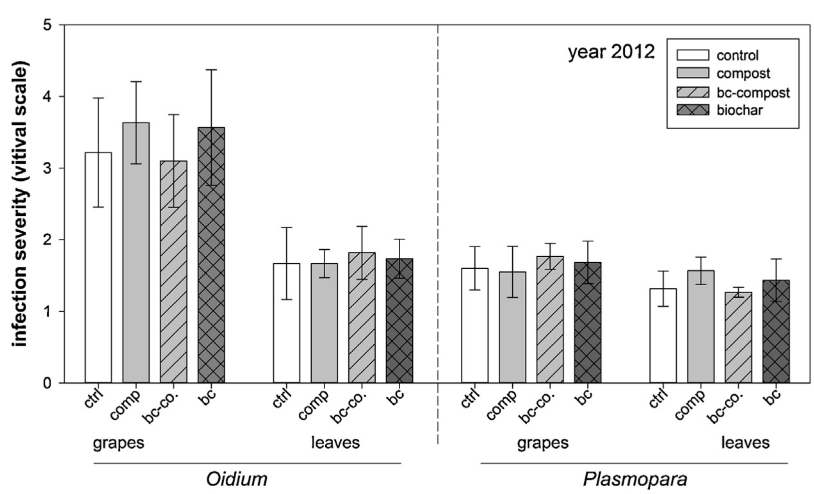

Fig. 1. Infection rate of *Plasmopara viticola* and *Oidium tuckerii* on leaves and grapes in 2012. Intensity of infection classified according to the VITIVAL-scale from 1 to 8 for plasmopara on berries and from 1 to 6 for oidium on grapes and for both pathogens on leaves ($n = 5$).

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Table 3
Concentration of quality relevant grape constitutes for 2013: numbers represent the mean ± SE (n = 5). The treatments with different letters denote significantly difference at $p < 0.05$.

	Control	Biochar	Compost	Biochar-compost
Total sugar ($g\,l^{-1}$)	221.7 ± 6.17a	217.8 ± 3.64a	217.9 ± 3.86a	221.6 ± 3.52a
Ammonium ($mg\,l^{-1}$)	75.6 ± 5.39a	79.4 ± 11.64a	81.4 ± 12.4a	81.8 ± 8.66a
NOPA ($mg\,l^{-1}$)	168.2 ± 28a	163.4 ± 24.84a	187.8 ± 41.84a	173.2 ± 23.34a
Total acidity ($g\,l^{-1}$)	7.92 ± 0.43a	8.26 ± 0.44a	8.26 ± 0.42a	8.02 ± 0.46a
Tartaric acid ($g\,l^{-1}$)	6.5 ± 0.47a	6.84 ± 0.14a	6.58 ± 0.42a	6.34 ± 0.21a
Malic acid ($g\,l^{-1}$)	3.98 ± 0.48a	4.1 ± 0.42a	4.44 ± 0.48a	4.2 ± 0.5a
Potential alcohol (%)	13.2 ± 0.37a	12.97 ± 0.22a	12.97 ± 0.23a	13.19 ± 0.21a
Glucose to fructose ratio	0.94 ± 0.01a	0.94 ± 2.42a	0.95 ± 0.01a	0.94 ± 0.01a
Glycerin ($g\,l^{-1}$)	0.34 ± 0.08a	0.3 ± 0.09a	0.28 ± 0.08a	0.32 ± 0.04a
Gluconic acid ($g\,l^{-1}$)	0.96 ± 0.2a	1.04 ± 0.29a	1.04 ± 0.25a	0.98 ± 0.2a
Volatile acidity ($g\,l^{-1}$)	0.182 ± 0.03a	0.194 ± 0.04a	0.204 ± 0.04a	0.19 ± 0.05a

4.3. Effects on grape and wine quality

As the economic output of wine producers is often preponderantly determined by the quality of their wines, the influence of an amendment on the wine quality will be the most decisive factor for the winegrower. In 2011 the pH of the must was significantly higher ($p < 0.05$) in both biochar treatments (Table 2), which could be due to earlier ripening (Hellman, 2004). In 2013 the pH of the must did not vary significantly between the treatments but total acidity of the must still showed a tendency ($p = 0.057$) to be higher in the biochar treatment compared to the control treatment, though not in the bc-compost treatment. In the case of Pinot noir in this vine-growing region this is not detrimental, but it may be negative in other more southern vineyards where low acidity causes wine quality problems. If biochar amendments cause accelerated development and ripening, as observed in sunflower by accelerated protein turnover (Noguera et al., 2012), it may warrant further studies.

The NOPA concentration of the grapes is of foremost importance for the must fermentation, as it is a limiting element for yeast nutrition. Although supplemental yeast nutrition is permitted and more and more common, especially in the dryer vine growing regions, it is not desirable for high quality wines as it changes the aromatic expression of the wines (Vilanova et al., 2007). However, whereas the results of the pooled samples of 2011 (Appendix Table 4) suggested that NOPA might be increased in the compost and in the bc-compost treatments, the statistical more relevant results of the harvest 2013 did not show any significant difference in the NOPA values.

As none of the other investigated grape quality parameters (see Tables 2 and 3) did show any significant difference neither, no direct influence of the biochar to the wine quality can be deduced.

4.4. Effects on plant health

As viticulture presents the highest yearly amounts of fungicides used per hectare within the agricultural sector (Garrigou et al., 2012), the induction of plant resistance through biochar soil amendments (Graber and Elad, 2013) would be especially welcome in order to reduce the usage of fungicides and its associated environmental hazards. However, no effects of biochar on plant health were detected (Fig. 1). As shown by Graber and Elad (2013), the eliciting effect on induced plant resistance is most likely due to DOC of the biochar, a secondary product of the pyrolysis process. The biochar-derived DOC is very likely partly degraded during the composting process; moreover it is probably also rapidly degraded in active soil (Zimmerman and Gao, 2013), so that it will not reach the depth of the main vine roots.

5. Conclusion

In the special case of a calcareous SOC-poor vineyard soil in a temperate climate, biochar and biochar-compost did not show relevant effects on plant growth parameters of vine or vine health; neither did pure compost amendment without biochar. Minor effects on grape quality were present in the first year, though not in the second and third year. Thus our initial hypotheses (1) and (3) were not met, which may have been partly due to favourable, unrestrictive soil and climatic conditions. In the first year, the application of non-composted biochar showed some negative effects compared to the biochar-compost. These differences levelled out in the second and third year, meeting partly hypothesis (2).

For further biochar trials in vineyards it could be advantageous to incorporate (nutritive enhanced) biochar or biochar-substrates in trenches of 30–50 cm on one or both sides of the vines instead of applying the substrates homogenously over the entire surface of the plots. Higher concentrations of biochar or biochar containing substrate closer to the main roots of the vines could increase their effect on the vines, creating spots with higher water retention and nutrient concentration (Blackwell et al., 2010; Graves, 2013). Moreover, during the course of the study, no particular drought period occurred. Therefore potential increases in the plant available water supply and alleviation of drought stress, as observed by Baronti et al. (2014) with pure biochar, could not have come into effect.

A large number of studies have documented a reduction in the bioavailability of organic pesticides following biochar or charcoal application in agricultural soils (Gomez-Eyles et al., 2013; Wang et al., 2010; Yu et al., 2010; Yang et al., 2013). Ventura et al. (2013) and others have shown that biochar may reduce nitrate leaching in orchards which is comparable to the situation in vineyards. Therefore even if biochar does not have significant positive effects on yield and quality, the application of biochar might become a suitable tool to improve ecosystem services and to decrease the environmental impact of pesticides, heavy metals (especially the widely used copper, in particular in organic viticulture), herbicides, and chemical fertilizers.

Acknowledgements

We thank Carbon Terra GmbH for supplying the biochar and Delinat AG for its generous donation to this project, and Matthias Schröder, Samuel Kipfer and all interns for their thorough help during the set-up of the trial, the numerous sample-takes and analyses.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2014.04.001.

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Please cite this article in press as: Schmidt, H.-P., et al., Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality. Agric. Ecosyst. Environ. (2014), http://dx.doi.org/10.1016/j.agee.2014.04.001

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