Agriculture, Ecosystems and Environment 201 (2015) 20–25

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany

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ARTICLE INFO

Article history:
Received 10 September 2014
Received in revised form 17 November 2014
Accepted 18 November 2014
Available online 27 December 2014

Keywords:
Biochar
Climate change adaptation
Sustainable viticulture
Grape quality

ABSTRACT

Biochar application to agricultural soils has proved to substantially modify the plant–soil–water relationship and lead mostly to a quantitative increase in agricultural production through physical, chemical and biological mechanisms. Nevertheless, the impact of biochar on qualitative traits of agricultural production needs to be further assessed.

The effect of biochar application on vine yield and grape quality parameters is here investigated in a non-irrigated vineyard in Tuscany (central Italy). Results from four harvest-years showed a higher productivity, up to 66%, of treated plots with respect to their controls, while no significant differences were observed in grape quality parameters. The observed increase in productivity was inversely correlated with rainfall in the vegetative period, confirming the key role of biochar in regulating plant water availability. These findings support the feasibility of a biochar-based strategy as an effective adaptation measure to reduce the impact of water stress periods with no negative effects on grape quality.

1. Introduction

Biochar application to agricultural soils has recently emerged as an effective win-win strategy to steadily sequester carbon into agricultural soils, produce renewable energy and increase crop yields (Woolf et al., 2010). The mechanisms involved in the agronomic benefits of biochar are chemical, physical and biological. Biochar is known to decrease nutrients leaching (Güereña et al., 2013) and diminish the bioavailability of heavy metals (Park et al., 2011), improve soil water holding capacity (Glaser et al., 2002) and plant water availability (Baronti et al., 2014), improve soil structure (Case et al., 2012) and stimulate soil microbial activity (Kolb et al., 2009; Rutigliano et al., 2014), in general leading to increases in crop productivity that have been estimated to be as high as 10% across different crops, soils, biochar types and application rates (Jeffery et al., 2011). It is worth noting that despite many experiments observed positive effects of biochar application on crops, most of them do not refer to long-term experiments (Lorenz and Lal, 2014) and in some cases biochar benefits demonstrated to have a transient nature (Quilliam et al., 2012).

Furthermore, although a quantity of literature has been produced describing the agronomic effect of biochar on herbaceous crops, few studies were dedicated to tree crops, because of the difficulties to perform representative experiments in controlled environment, and the longer time required to produce detectable effects on species with a largely developed root system. In particular only few studies exist on the impact of biochar on vineyards in the primary literature (Baronti et al., 2014; Schmidt et al., 2014), while the importance of enlarging our knowledge on the response of different crops in different soils/climate systems to the application of different biochars has been continuously stressed and identified as a research priority (Mukherjee and Lal, 2014).

Moreover, few researches have assessed the impact on quality of production. Vaccari et al. (2011) in an experiment on durum wheat in central Italy observed an increase up to 30% in above ground biomass and yield without any significant effect on grain quality defined as grain protein content.

The aspect of quality has a particular relevance for viticulture that is known to be highly sensitive to inter-annual climate variability. Grape quality parameters substantially affect the value of production, delineate the distinctive character of a *terroir* and define the rating of a vintage with respect to another. Moreover, in

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http://dx.doi.org/10.1016/j.agee.2014.11.021
0167-8809/

recent decades global climate changes have been a major cause of concern between winegrowers because of the rise in mean air temperature and of the increase of frequency and intensity of extreme weather events such as droughts and heat-waves. Those changes are projected to increase in the forthcoming decades causing a shift in the viticulture suitability of many productive regions (Hannah et al., 2013; White et al., 2006) and forcing winegrowers to adopt reactive and/or anticipatory adaptation measures (Nicholas and Durham, 2012).

Baronti et al. (2014), who applied a large volume of biochar for two consecutive seasons to a non irrigated vineyard in Tuscany (central Italy), reported an increase in soil water content, a reduction of plant water stress and an increase of photosynthetic activity during drought. This suggests that the application of biochar to vineyards is a feasible adaptation strategy to reduce the impact of severe water stress periods without recurring to irrigation. Nevertheless, despite these positive results some concerns still remain on the potential impact of such a strategy on quality of production. The only attempt to explore the relation between biochar application and grape quality was made by Schmidt et al. (2014) who applied low biochar rates (8 t ha^{-1}) to a vineyard near Valais and did not observe significant variations in plant growth nor changes in grape quality parameters.

The present work aims to assess the impact of biochar on vine yield and grape quality parameters in four harvests and is based on the same field experiment described in Baronti et al. (2014). In order to rule out eventual transient effects, after a first application, biochar was re-applied on part of the experimental layout one year later.

2. Materials and methods

The experiment was carried out on a vineyard at “La Braccesca Estate” (Marchesi Antinori srl, www.antinori.it) near Montepulciano in central Italy (Lat. 43°10′15″N; Long. 11°57′43″E; elevation 290 m above sea level). The vineyard (*Vitis vinifera* [L.]) was planted in 1995 (cv. Merlot, clone 181; rootstock 3309 Couderc) and the trellis system is a single curtain with plant-row spacing of 0.8 m and 2.5 m, respectively. Rows orientation is East–West, inter-rows are partially covered with spontaneous grass, and tilled with a chisel plow in the March–June period. The vineyard is not irrigated and it is fertilized with an inorganic fertilizer (15.0.26) twice per year (in November and April) at a rate of 120 kg ha^{-1}. Soil is acid, shallow and sandy-clay-loam textured (USDA, 2005) (Table 1) and is highly compacted below 0.4 m depth.

Table 1
Soil properties of the experimental vineyard.

	Unit	Value
Sand[a]	g kg^{-1}	450
Silt	g kg^{-1}	200
Clay	g kg^{-1}	350
Bulk density	t m^{-3}	1.45
OC[b]	g kg^{-1}	4.7
N[c]	g kg^{-1}	0.46
K available	mg K_2O kg^{-1}	192
Ca available	mg CaO kg^{-1}	1454
Mg available	mg MgO kg^{-1}	939
Na	mg Na kg^{-1}	97
CEC[d]	meq 100 g^{-1}	25.7
pH[e]		5.37

[a] Refers to fine (<2 mm) texture fraction.
[b] Organic carbon (OC) content was determined using a CHN auto-analyser (CHN 1500, Carlo Erba).
[c] Nitrogen (N) content was determined using a CHN auto-analyser (CHN 1500, Carlo Erba).
[d] Cation exchange capacity (CEC) was determined using the NH4OAc method.
[e] pH was measured in a 1:2.5 (mass/vol) soil solution.

Biochar was applied with two treatments, in five replicates randomly distributed, as follows: 22 t ha^{-1} of biochar applied in 2009 (B); 22 t ha^{-1} in 2009 and further 22 t ha^{-1} in 2010 (BB) and control untreated plots (C). Water content of biochar was 25%, therefore each application corresponded to 16.5 t ha^{-1} of dry biochar. Each plot (15 in total) had a surface area of 225 m^2 (7.5 m in width and 30 m in length) including 4 rows and 3 inter-rows. Biochar was superficially applied to soil of vineyard inter-row with a spreader and partially buried with a chisel plow tiller to 0.3 m depth.

Meteorological parameters were registered by an automatic weather station placed nearby the vineyard (Fig. 1).

The biochar used in the experiment is a commercial low temperature (500°) slow pyrolisis biochar derived from orchard

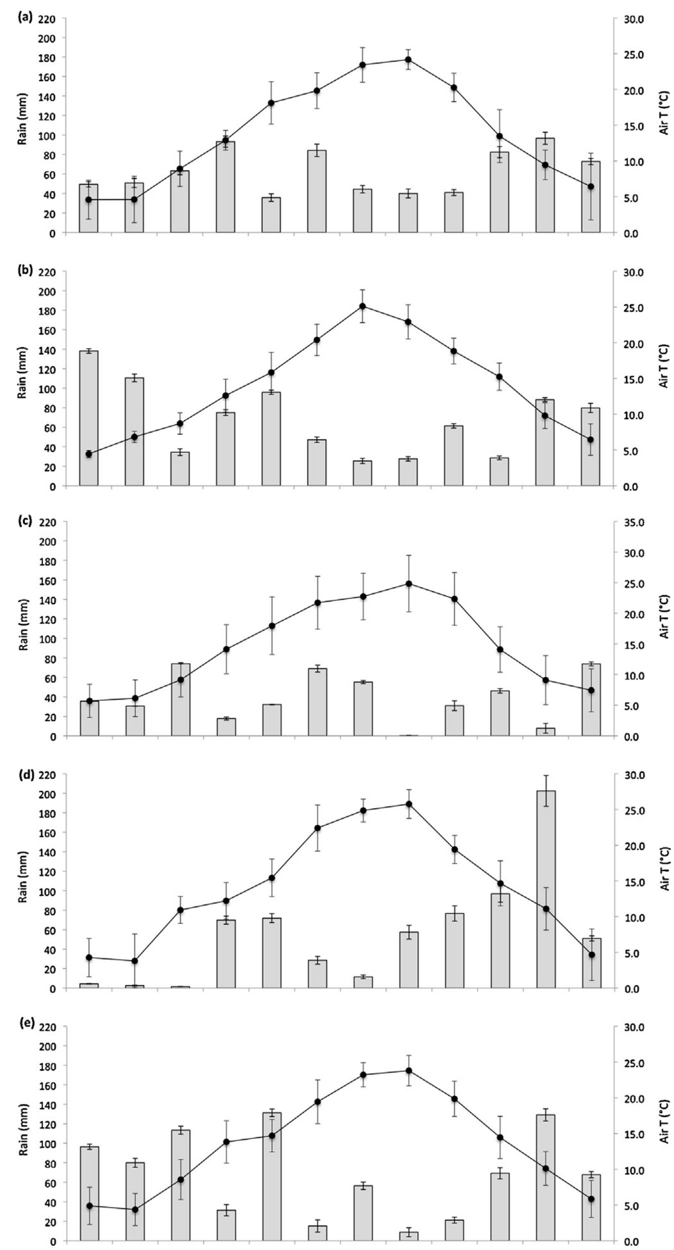

Fig. 1. Summary of monthly cumulated rainfall (colums, left axis) and monthly average temperature (dots, right axis) for the years 2009 (a), 2010 (b), 2011 (c), 2012 (d), 2013 (e). Error bars represent standard error.

Table 2
Chemical and physical characteristics of biochar applied in the field experiment (modified from Baronti et al., 2014).

	Unit	Value
C	%	77.81
N	%	0.91
Al	mg kg^{-1}	268
C/N	–	63.53
Ca	mg kg^{-1}	25000
Cu	mg kg^{-1}	97
Fe	mg kg^{-1}	333
K	mg kg^{-1}	13900
Mg	mg kg^{-1}	28700
Mn	mg kg^{-1}	84
Na	mg kg^{-1}	11900
P	mg kg^{-1}	23300
S	mg kg^{-1}	481
Zn	mg kg^{-1}	104
pH	–	9,8
CEC	(cmolc/kg)	101
Max water absorption	g g^{-1} of d.m.	4.53
BET	m^2 g^{-1}	410 ± 6
Total porosity	mm^3 g^{-1}	2722
Transmission pores	mm^3 g^{-1}	318
Storage pores	mm^3 g^{-1}	1997
Residual pores	mm^3 g^{-1}	406
Particle size distribution (mm):		
50–20	%	4.45
20–10	%	12.1
10–8	%	13.1
8–4	%	10.36
4–2	%	19.85
2–1	%	24.2
<1	%	15.94

pruning feedstock provided by Romagna Carbone (Bagnacavallo, Ravenna, Italy). Biochar chemical and physical characteristics are summarized in Table 2, analytical methodologies for biochar characterization are provided in Baronti et al. (2014).

A first experiment has been made on this vineyard specifically focused on soil–plant–water relationships (Baronti et al., 2014). For these purposes soil was sampled 4 times in 2011 to assess gravimetrically the soil water content and to calculate soil bulk density. Soil water retention curves were obtained with pressure plates and soil hydrophobicity was assessed with the water drop penetration test (WDPT); ecophysiological measurements of leaf water potentials and leaf gas exchange were made in each experimental plot in summer 2011 on two cloud-free days. The methodology and protocols for these measurements are extensively described in Baronti et al. (2014).

Grapes were sampled in 2009 (only B and C plots), and in 2010, 2012 and 2013 (B, BB and C plots). For quantitative analysis 5 plants for each plot were hand-harvested (a total of 30 sampled plants in 2009 and 45 sampled plants in 2010, 2012, 2013), clusters per plant were counted and weighted individually, a sample of 50 berries for each plot was weighted and used to calculate skin-to-pulp ratio and number and weight of seeds (only in 2012 and 2013).

From the harvested plants a sample of 2.5 kg of grapes was taken for the analysis of following quality parameters: soluble solids (expressed as °Brix), total acidity (expressed as g l^{-1}of tartaric acid) pH, and total anthocyanins (mg l^{-1}). Sampled clusters were crunched with a laboratory press and musts analysed with a Foss analyser (WineScan^{TM}, Foss, Denmark).

Statistical analysis was performed in R statistical environment (R development team, 2014). Post-hoc comparison adopting one-way ANOVA scheme were made with "multicomp" R package (Hothorn et al., 2008). Tukey HSD testing framework was used to verify the significance of differences between treatments (C, B, BB).

3. Results

The addition of biochar to soil caused a substantial and significant change in soil physical characteristics with a decrease of soil bulk density and an increases in available soil water content in treated soils compared to control soils (from 3.2% to 45% in the 22 and 22 + 22 t ha^{-1} application rates, respectively). These changes translated into increased leaf water potential (24–37%) during droughts (Baronti et al., 2014).

Results of fruit sampling made at harvest indicate that grape yield per plant significantly increased in biochar treated plots in all harvest years (Table 3). The proportional increase relative to the control ranged from 16% to 66% lasting across the four years of the experiment; the biochar re-application treatment did not result in any significant improvement.

The number of clusters per plant was not affected, while the average cluster weights were always significantly increased, except in the first year, with a maximum of 46% in BB plots in 2012 (Table 4); no significant differences in average cluster weight were observed between B and BB treatments. Plants from treated plots showed significantly bigger berries in 2012 (B) and in 2013 (both B and BB), with a maximum increase of 14.8% in BB plot in 2013, compared to controls (Table 5).

Analysing the yield difference in the four harvests between the control and the biochar treatments (pooled together), the observed increase in productivity was inversely correlated (R^2 = 0.75) with the precipitation recorded during the growing season (Fig. 2). The effect of biochar on yield was therefore higher in the years with lowest rainfall.

Grape quality parameters show a high inter-annual variability confirming the importance of climatic drivers on grapevine quality. The observed increase of productivity did not correspond to a significant variation in any of the selected quality parameters between treatments and their controls (Table 6).

The analysis of seeds made in 2012 and 2013, highlighted a significant increase in number of seeds per berry (up to 29.8% for BB in 2013) and total seed weight per berry (up to 28.7% for B in 2012) in treated plots respect to the control, with no changes in average seed weight (Table 7).

4. Discussion

Water availability plays a key role in determining the quality and quantity of most agricultural production in the Mediterranean region and based on our results this includes vineyard production. Water deficits are known to alter fruit mass and composition mainly through direct effects on the berry size; in general higher

Table 3
Grape yield per plant (fresh weight). Δ*y* is the % yield variation in biochar treated plots with respect to the control (s.e. is the standard error). All the values are average of 25 plants for each treatment per year. Values followed by the same letters are not statistically different at P = 0.05 by the Student–Newman–Keuls test.

Year	Treat.	Yield ± s.e (kg plant^{-1})	Sign. code	Δ*y* (%)
2009	C	1.36 ± 0.08	a	
	B	1.63 ± 0.09	b	20
2010	C	1.34 ± 0.09	a	
	B	2.12 ± 0.19	b	58.1
	BB	1.90 ± 0.16	b	42.3
2012	C	1.05 ± 0.09	a	
	B	1.62 ± 0.14	b	54.6
	BB	1.75 ± 0.14	b	66.8
2013	C	1.44 ± 0.11	a	
	B	1.68 ± 0.11	ab	16.1
	BB	1.95 ± 0.15	b	35.3

Table 4
Number of clusters per plant and average cluster fresh weight at harvest. Δy is % of variation in biochar treated plots respect to the control (s.e. is the standard error). Values are average of 25 plants for each treatment. Values followed by the same letters are not statistically different at $P = 0.05$ by the Student–Newman–Keuls test.

Year	Treat.	N° clusters plant^{-1} ± s.e.	Sign. codes	Δy (%)	Avg. cluster weight ± s.e (g)	Sign. codes	Δy (%)
2009	C	14.47 ± 0.40	a		106.44 ± 5.99	a	
	B	14.33 ± 0.51	a	−1.0	115.94 ± 5.46	a	8.9
2010	C	15.64 ± 0.73	a		85.56 ± 2.47	a	
	B	18.12 ± 0.97	a	15.9	116.49 ± 3.39	b	36.2
	BB	17.90 ± 1.04	a	14.5	106.37 ± 3.53	b	24.3
2012	C	14.80 ± 0.83	a		71.02 ± 2.25	a	
	B	16.22 ± 0.92	a	9.6	100.33 ± 3.09	b	41.3
	BB	16.82 ± 1.08	a	13.6	104.35 ± 2.84	b	46.9
2013	C	18.00 ± 1.15	a		80.05 ± 2.01	a	
	B	18.12 ± 0.96	a	0.7	92.53 ± 2.42	b	15.6
	BB	18.76 ± 1.44	a	4.2	99.72 ± 2.53	b	24.7

water availability translates into increased production with detrimental effect on key grape quality parameters (Van Leeuwen et al., 2009; Bramley et al., 2011). With full water availability, photosynthetic activity is not constrained by stomata closure and grape sugar levels are lower due to competition for carbon substances between berry and shoots and because of the greater sugar dilution in a bigger berry associated to increased water content; on the contrary, in mild water deficit conditions ripening is promoted by the production of abscisic acid in roots and vine produces smaller berries higher in sugar, anthocyanins and tannins content (Van Leeuwen et al., 2009).

In our experiment, biochar application increased soil water content and plant available water, this is likely to have driven the substantial increase in productivity (yield, average cluster weight and berry size) in all harvests. This effect was higher in the years with lowest rainfall, convincingly supporting the idea of a positive regulation effect of biochar in case of water shortages. Unexpectedly, no significant effects were observed on key grape quality parameters, this suggests that the increased plant water availability due to biochar has a complex mechanism of action on plant physiology and involves an effect on tissues formation. In fact, it is recognized that the consequences of changes of berry size on overall fruit quality are not linear and that the timing of water stress affects the mass ratio of berry seeds, skin and pulp (Roby and Matthews, 2004); early water deficits (before *veraison*) may have an effect on the final cell number by reduced growth of mesocarp tissues (Considine and Knox, 1981); later on, during ripening, water stress can affect cell extension and overall berry hydration. The observed significant increase in seed mass, in response to an increased number of seeds per berry (from 1.6 to 2.02 in 2012 and from 1.45 to 1.88 in 2013 for C and BB treatments, respectively), confirms the key role of prior-to-veraison water stress in the fruit set and tissue formation (Roby and Matthews, 2004; Korkutal et al., 2011).

Grape fertility is also driven by other factors that could have been influenced by biochar, such as the nitrogen availability in the preceding season (Duchene et al., 2001), when it is well known that biochar affects nitrogen cycling and reduces its leaching (Ventura et al., 2013), and by temperature regimes near flowering (Ebadi et al., 1996) when it was proved that the changes of soil reflectivity (albedo) that follows biochar application may affect energy fluxes partitioning with a positive increase of soil temperatures (Genesio et al., 2012) and a consequent enhanced temperature regime at canopy level.

Biochar application is therefore likely to have driven the final fruit composition and mass through multiple mechanisms with different timing of action, namely (i) a reduction in nitrogen leaching in the preceding season that promoted fruit set and seeds number, (ii) an increase of temperature regimes near flowering that favoured grape fertility (iii) a reduction of water stress in pre-veraison that favoured multiplication of tissues cells and therefore the thickness of skin and (iv) a reduction in evaporative loss of

Table 5
Fresh weight of 50 berries at harvest. Δy is the %variation in biochar treated plots with respect to the control (s.e. is the standard error). Values followed by the same letters are not statistically different at $P = 0.05$ by the Student–Newman–Keuls test.

Year	Treat.	Fresh weight 50 berries ± s.e (g)	Sign. codes	Δy (%)
2010	C	63.20 ± 5.28	a	
	B	66.21 ± 5.79	a	4.8
	BB	67.02 ± 5.93	a	6.0
2012	C	46.92 ± 1.12	a	
	B	51.52 ± 1.46	b	9.8
	BB	49.40 ± 1.12	a	5.3
2013	C	81.20 ± 2.52	a	
	B	88.40 ± 2.50	b	8.9
	BB	93.20 ± 3.14	b	14.8

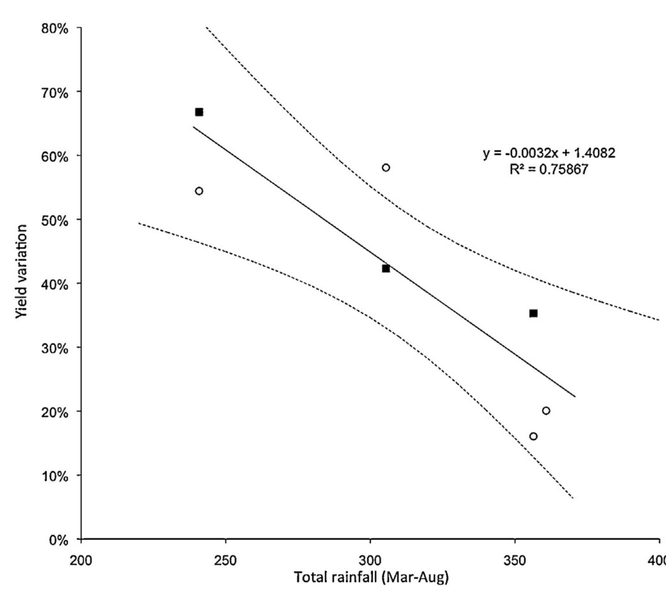

Fig. 2. Regression between total rainfall in the vegetative period (March–August) and the % yield variation of treated plots versus control (BB–C = black blocks; B–C = white circles). Trend line (solid, black) pools together BB and B data. Dashed lines represents the 95% confidence interval.

Table 6
Grape quality parameters (°Brix; total acidity: AT; pH; °Brix/AT; total anthocyanins: ANT) at harvest for C, B and BB treatments in 2009, 2010, 2012 and 2013. Values followed by the same letters are not statistically different at $P = 0.05$ by the Student–Newman–Keuls test.

Year	Treat.	°Brix	Sign. codes	AT	Sign. codes	pH	Sign. codes	°Brix/AT	Sign. codes	ANT	Sign. codes
2009	C	24.65 ± 0.33	a	5.54 ± 0.19	a	3.42 ± 0.01	a	4.47 ± 0.14	a	1123 ± 44	a
	B	23.95 ± 0.53	a	5.56 ± 0.18	a	3.42 ± 0.02	a	4.33 ± 0.19	a	1186 ± 73	a.
2010	C	24.74 ± 0.2	a	6.82 ± 0.19	a	3.32 ± 0.01	a	3.64 ± 0.08	a	1024 ± 24	a
	B	25.02 ± 0.24	a.	7.3.2 ± 0.47	a.	3.36 ± 0.01	a	3.49 ± 0.25	a	1045 ± 41	a
	BB	24.82 ± 0.22	a	6.64 ± 0.34	a	3.34 ± 0.01	a	3.78 ± 0.22	a	1019 ± 29	a
2012	C	24.32 ± 0.12	a	4.42 ± 0.05	a	3.65 ± 0.01	a	5.50 ± 0.06	a	937 ± 48	a
	B	24.08 ± 0.26	a	4.22 ± 0.09	a	3.62 ± 0.02	a	5.71 ± 0.12	a	949 ± 75	a
	BB	23.92 ± 0.26	a.	4.1 ± 0.13	a	3.62 ± 0.02	a	5.86 ± 0.18	a	994 ± .51	a
2013	C	23.51 ± 0.07	a	5.83 ± 0.14	a	3.36 ± 0.01	a	4.04 ± 0.11	a	1143 ± 38	
	B	23.23 ± 0.17	a.	6.08 ± 0.12	a.	3.36 ± 0.01	a	3.83 ± 0.09	a	1038 ± 68	a
	BB	23.19 ± 0.28	a	5.87 ± 0.14	a	3.39 ± 0.01	a	3.96 ± 0.13	a	1001 ± 70	a

berry in the latest phases of ripening due to the higher plant water availability.

The ensemble of those mechanisms could explain the unexpected results in grape quality parameters where, despite the diminished water availability of non-treated vines, the berries of the control vines did not show neither significantly higher sugars nor an increase in anthocyanin concentration. Indeed, the observed differences in yield did not correlate with changes in grape quality parameters; coherently, similar results were found in the skin-to-pulp ratio where no-significant differences between treatments were observed (data not shown).

The lack of significant effect on grape quality parameters is in agreement with the findings of Schmidt et al. (2014) that did not observe any significant difference between treatments and controls after the application of 8 t ha^{-1} of biochar to a vineyard in Valais, although the differences in soil and biochar application rate and the absence of water limiting conditions in the Valais vineyard limits the possibility to compare the two experiments.

The absence of significant yield differences between the two biochar treatments suggests that a saturation response was already reached at the application of 22 t ha^{-1}, in agreement with the observed saturation on plant water relationships (Baronti et al., 2014). In the specific conditions of our experiment, the biochar saturation threshold is likely to be lower than 22 t ha^{-1}. Moreover, in our experiment, biochar benefits did not have a transient nature as observed elsewhere after biochar reapplication (Quilliam et al., 2012) but, on the contrary, its effect was maintained for at least four years.

These findings are particularly relevant when seen in the context of the expected changes in climate and the required adaptation strategies that should be urgently considered for a sustainable viticulture (Webb et al., 2012; Diffenbaugh et al., 2011). Indeed, the quality and quantity of grapevine production remains strictly linked to seasonal climate variability. While it has been proven that moderate water stress might lead to improved grape quality, excessive stress conditions are known to lead to an imbalance of the sugar/acidity ratio and to an impairment of the dynamic of polyphenols accumulation, causing major difficulties in the identification of the optimal harvest time (Jones et al., 2005). For this reason irrigation has been considered a key strategy to reduce the impact of climate variability and to enhance quality also through regulated deficit irrigation and partial root drying approaches (Bindon et al., 2008; Romero and Martinez-Cutillas, 2012). But irrigation inevitably competes with other civil and industrial water uses and water availability may become scarce especially if the expected reduction in precipitation in some important viticulture areas of the world will be confirmed (Hannah et al., 2013). In addition, irrigation is known to have negative impact on soil erosion and groundwater quality and might remain banned in many AOC areas (Appellation d'Origine Controllée) or limited to extreme emergency situations. The use of biochar as a soil amendment could therefore become an effective adaptation strategy and alternative to irrigation, to enhance the drought tolerance of vineyards leading to substantial increases in yields without any evident detrimental effect on quality parameters.

The definition of such an adaptive strategy certainly calls for further studies to provide more focused insights in molecular and physiological mechanisms associated to biochar application to vineyards and to better account for the biochar specificity of action in different areas regions and soils.

In particular the increased grape fertility, expressed by the number of seeds per berry, observed in our experiment, must be investigated further to confirm the existence of mechanisms other than water and nutrient availability with particular reference to microbial activity and hormonal pathways (Gomez et al., 2014; Spokas et al., 2010). Moreover, changes in the susceptibility of biochar-treated vineyards to pests and diseases should also be investigated in detail, as recent transcriptional studies have shown that biochar-driven growth stimulation in model plants is associated to changes in defence genes expression (Viger et al., 2014).

Table 7
Seeds number for 50 berries (SN), seeds dry weight for 50 berries (SDW) and average seed weight (ASW) for the control (C) and treated plots (B and BB) in 2012 and 2013. Δy is the SN, SDW and ASW variation (%) in biochar treated plots respect to the control (s.e. is the standard error). Values followed by the same letters are not statistically different at $P = 0.05$ by the Student–Newman–Keuls test.

Year	Treat.	SN ± s.e.	Sign. codes	Δy (%)	SDW ± s.e. (g)	Sign. codes	Δy (%)	ASW ± s.e. (g)	Sign. codes	Δy (%)
2012	C	82.20 ± 6.37	a		2.03 ± 0.13	a		$2.48\ 10^{-2} \pm 4.19\ 10^{-4}$	a	
	B	106.10 ± 5.64	b	29.0	2.62 ± 0.14	b	28.7	$2.46\ 10^{-2} \pm 1.58\ 10^{-4}$	a	−0.7
	BB	102.90 ± 5.13	ab.	25.2	2.45 ± 0.14	ab	20.7	$2.38\ 10^{-2} \pm 4.95\ 10^{-4}$	a	−4.2
2013	C	72.60 ± 3.33	a		2.33 ± 0.11	a		$3.21\ 10^{-2} \pm 7.49\ 10^{-4}$	a	
	B	80.20 ± 3.02	a	10.5	2.50 ± 0.08	a.	7.0	$3.11\ 10^{-2} \pm 4.93\ 10^{-4}$	a	−3.1
	BB	94.20 ± 2.15	b	29.8	2.89 ± 0.10	b	23.8	$3.06\ 10^{-2} \pm 5.49\ 10^{-4}$	a	−4.8

5. Conclusions

The likely consequences of using biochar as a soil amendment to reduce water stress in viticulture do require some careful analysis and detailed impact assessment. Our study dealt specifically with the assessment of the impact of high rates of biochar application on vine yield and grape quality parameters. The main conclusions are that:

i) biochar substantially increased vineyard production in all harvest-years; this yield increase was inversely correlated with rainfall in the vegetative period, thus highlighting that the effect of biochar was higher in dry years and emphasising the role of biochar in increasing plant water availability;
ii) despite the yield increase, no detrimental effects on key grape quality parameters were observed; the absence of qualitative differences suggests that biochar mechanisms of action is more complex than being the direct consequence of the improved water status and, although some hypothesis can be formulated, the full understanding of such mechanisms requires further investigations;
iii) a biochar based strategy could be effectively adopted in vineyards in drought prone areas as an alternative to irrigation.

Finally, the profiling of wine quality attributes following biochar application needs to be further explored in long term experiments by means of sensory panels and testing this strategy in other soils and wine regions.

Acknowledgements

The authors acknowledge the “Marchesi Antinori – La Braccesca Estate” for hosting the experiment and in particular Christian Zulian, Samuele Collini and Giancarlo Certini for their technical support in field campaigns and Alfonso Crisci (IBIMET CNR) for the support in defining the statistical approach. This work contributes to the Eurochar project (FP7-ENV-2010 ID-265179) and Agro-PyroGas project (Regione Toscana POR CRO FSE 2007–2013 asse IV). The Italian Biochar Association (ICHAR www.ichar.org) is also acknowledged.

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