

Establishment of a commercial organic hopyard in a Mediterranean environment: Production attributes and their relationship with soil texture

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ABSTRACT

The cultivated hops are recently moving towards new growing areas in Southern Europe, boosted by the increasing number of craft breweries and by the higher vulnerability to climate change observed, for this crop, in the traditional growing regions. Despite this clear market and geographic trend, there is a lack of knowledge about pedoclimatic needs and agronomic performances of hops grown in the Mediterranean environment. Particularly, the agronomic potential of a new hopyard during its establishment period is poorly studied even in traditional growing zones. Moreover, a restricted number of plants were usually sampled to gather the few data available, thus leading to a probable overestimation of yield performance. A commercial organic hopyard in central Italy was established and a 2-year (2018–2019) field experiment was set-up to accurately investigate the cone and shoot yield potential of cultivar ‘Cascade’ and to understand how such yields are related to each other and to soil texture. Hop plants were two-years old when the experiment started; plant population was 4,000 plants ha⁻¹. Forty points within the hopyard were sampled for soil analysis and yield traits. Data were analyzed accounting for spatial dependence of the sampling points. Results show a negative relation between clay content in the soil and hop yields, even though it was significant only in the exceptional rainy season of 2018. Shoot and cone yield were positively and strongly related, suggesting the green shoot yield in spring as a good predictor of hop production. Both shoot and cone yield significantly increased from the second to the third year (+11% and +16%, respectively); however, the unseasonably high rainfall of 2018 probably lowered the yield of the first experimental year. Cone yield attained over this 2-year study (1.24 t ha⁻¹ and 1.44 t ha⁻¹ for 2018 and 2019, respectively) was within the published ranges for mature plants. Similarly to cone production, shoot dry matter yield was lower in 2018 (197 kg ha⁻¹) than in 2019 (218 kg ha⁻¹). This study provides the first reliable information on both cone and shoot yield potential of a young organic hopyard under Mediterranean climatic conditions.

1. Introduction

The common hop (*Humulus lupulus* L.) is an industrial crop cultivated almost exclusively to meet the needs of the brewing industry. For this purpose, female inflorescences (commonly known as cones) represent the plant part having commercial value.

Global hop acreage constantly increased from 2012 to 2020. Total production and area harvested were near to 125,000 t and 67,000 ha in 2020, with an average cone yield of about 1.9 t ha⁻¹. The 2020 top

producing countries were the United States of America (47,090 t) and Germany (46,900 t). The European Union (EU-27), accounting for almost the half of the world hop production and acreage (61,510 t and 30,750 ha, respectively), is the hub of the global hop market (FAO, 2022).

The traditional hop growing zones are located mainly in Central Europe. From there, hop cultivation spread around the world, where climatic conditions met the plant needs (Neve, 1991). To flower and yield properly, hops require vernalization during winter dormancy, mild

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temperatures coupled with long days in spring, decreasing daylength in summer, sufficient moisture from irrigation or rainfall throughout the growing season, and dry weather during harvest time (Mozny et al., 2009; Neve, 1991; Sirrine, 2010). Consequently, hop cultivation thrived between 40° and 50° latitude, both North and South.

However, findings from a recent study demonstrated that photoperiod is the sole trigger factor for hop cone formation and that vernalization and rootstock dormancy have no effects on hop production and quality (Bauerle, 2019). This evidence opens the historical boundaries of hop cultivation and leads to speculate that global hop production could be profitably widened towards southern environments, still respecting the photoperiodic needs of the plant. Recently, Potopová et al. (2021) highlighted that the vulnerability of hop cultivation, due to hot and dry climatic anomalies, is becoming higher in northern Europe than in the South. The authors, analyzing 58 years (from 1961 to 2018) of weather and production data coming from the key hop-growing regions, showed that yields decreased more in Germany and Czech Republic than in any other country. Additionally, the risk of yield losses was found to be very high under the wet-cool conditions of August in Poland and United Kingdom. Indeed, wet-cool climatic conditions can damage hops by causing waterlogging, higher pest and pathogens pressure, and leaching of nutrients. Conversely, from the same study emerged that hop productivity in the southern growing countries, such as Spain, was more related to the advances in the agronomic techniques than to climatic events. Thus, in their conclusions, the authors hypothesized that, driven by the climate change scenario, the current regionalization of the European hop production might experience a new set up in the future.

Actually, the considerable growth that the craft beer sector experienced in the last decades had already caused the exploration of new growing areas in the southern part of Europe, such as Italy (Rossini et al., 2016; Ruggeri et al., 2018). This trend was further promoted by the interest of brewers in using locally grown hops having yield and quality attributes consistent with commercial hop varieties. In this respect, while many studies demonstrated the good aroma and flavor profile gained from hops cultivated in the Mediterranean environment (Forteschi et al., 2019; Marceddu et al., 2020; Mongelli et al., 2016; Mozzon et al., 2020), very few investigations attempted to estimate yield potential in the same climatic conditions (Rossini et al., 2016). Moreover, even though the demand for organic hops is rising (Turner et al., 2011), no studies have been published on the feasibility of organic hopyard establishment and its yield potential under Mediterranean climatic conditions.

The development of hop cultivation in the Mediterranean region is hindered by both structural and learning factors. Besides the almost total absence of harvesting and post-harvest machines, a lack of knowledge, regarding crop requirements and hopyard management practices, still exists (Rossini et al., 2021).

The first step before planting a new hopyard is to determine the soil physical and chemical properties. Recently, Afonso et al. (2020) suggested that several soil features such as pH, redox potential, clay content, organic carbon and nutrient interactions contributed to the weakness of mature hop plants in Portugal. Particularly, the authors associated the low vigor of plants to the poor drainage efficiency of the soils and irregular water distribution caused by the surface irrigation system. Furthermore, the same authors found a significant negative relation (Spearman correlation coefficient = -0.666^{**}) between clay content into the soil and cone yield (Afonso et al., 2021a), even with relatively low clay percentages (<20%), thus suggesting a strong effect of soil texture on hop productivity.

Establishing a hopyard requires a considerable investment in capital and labor before a crop is produced. The faster these costs are recovered through harvest, the earlier the hopyard becomes profitable. For this reason, the yield potential of hops soon after the planting year is a crucial information for both economic and agronomic considerations. Despite this, the productive performance of plants during the establishment period is probably the most overlooked aspect of hop

cultivation.

Usually, 3-year-old plants are considered mature (Adams, 2021). However, studies estimating cone production and quality in hop plants younger than 5 years were rarely conducted. Darby et al. (2014a) reported 207 and 400 lbs/acre (about 232 and 450 kg ha⁻¹, respectively) for two and three-year old plants of cultivar 'Cascade', organically grown in Alburgh, VT (U.S.A.). The same author showed the yield, gained from the same plants, to be increased up to 953 lbs/acre (about 1068 kg ha⁻¹), during the year four (Darby et al., 2014b). Recently, other American authors reported cone yield of 'Cascade' approaching 200 kg ha⁻¹, at the end of the planting year, in west-central Florida (Acosta-Rangel et al., 2021). In the Mediterranean environment, cone yield obtained from young plants of the same hop variety (e.g. 'Cascade') seems to be markedly higher than that gained in the United States. For example, three-year-old plants of cultivar 'Cascade', grown in Central Italy, yielded approximately 1 t ha⁻¹ of marketable cones (Ruggeri et al., 2018). However, the few experiments conducted to estimate the yield potential of hops under the Mediterranean climatic conditions relied on very few sampled plants, thus probably leading to an overestimation of cone production (Bavec et al., 2003). For these reasons, studies aiming at the acquisition of more reliable data, possibly from commercial hopyards, are not only warranted but also highly desired.

Besides cones, tender shoots resprouting each spring from the basal rootstock (i.e. perennial underground stem organs, crown, and accompanying roots), may be a source of additional income for hop growers working in those areas where the consumption of hop shoots is popular (Ruggeri et al., 2018). The sale of fresh shoots in small bundles (often directly in the farm) may help farmers to recover earlier the costs of hopyard establishment (spring shoots are regarded as the most expensive vegetable in the world). Hop shoots proved to have low lipid content and to be a good source of proteins, fibers, vitamins, and bioactive compounds (Rossini et al., 2020; Sanchez-Mata et al., 2012; Vidmar et al., 2019). Additionally, since the hop plant grows back from the basal organs every year, monitoring rootstock increase (through the measure of shoot biomass and number), during the establishment period (two or three years after planting), can help farmers and researchers to quickly identify the cultivars well adapted to the local pedoclimatic conditions.

The objective of this study was to accurately characterize, through spatialized data, the cone and shoot yield gathered from a real organic commercial hopyard in two subsequent years, under Mediterranean climatic conditions.

Moreover, the following hypotheses were tested:

- (1) a strong negative relation exists between clay content of the soil and cone and shoot production (Afonso et al., 2021a, 2020);
- (2) since shoot production can be considered a predictor of plant vigor, rootstocks having high shoot biomass production, result in high cone yield as well (Ruggeri et al., 2018).

The results would provide Mediterranean hop growers with novel and crucial information on agronomic potential of such a challenging crop.

2. Materials and methods

2.1. Location, experimental design and hopyard management

The experiment was carried out during two consecutive years, 2018 and 2019, in a certified organic commercial hopyard (0.6 ha) located at Lanuvio, near Rome, Central Italy (41° 37' N, 12° 40' E, altitude 86 m a.s.l.). Weather data of the two growing seasons are reported in Table 1.

The hopyard was planted in Autumn 2016 with plant rows oriented in an east northeast – west southwest direction. Rooted cuttings of cultivar 'Cascade' were used. Plant rows were spaced 2.5 m apart and plants 1 m apart along rows (4,000 plants ha⁻¹). The weight-bearing

Table 1

Monthly mean maximum, mean minimum, average air temperature, and rainfall during 2018 and 2019.

	Tmax (°C)		Tmin (°C)		Tavg (°C)		Rainfall (mm)	
	2018	2019	2018	2019	2018	2019	2018	2019
January	14.5	11.1	5.9	2.2	10.0	6.3	68.8	87.8
February	11.0	15.0	3.3	3.6	6.9	9.0	125.4	45.2
March	14.4	17.8	5.8	6.1	10.0	11.8	213.6	10.6
April	22.3	18.7	10.5	8.2	16.3	13.3	40.6	80.4
May	24.4	19.1	15.0	10.0	19.6	14.3	73.8	132.2
June	29.0	30.4	17.4	17.2	23.2	24.0	57.2	4.4
July	32.2	31.9	20.1	19.6	26.2	25.7	24.2	25.8
August	32.2	32.7	20.5	20.1	25.6	26.0	87.2	9.6
September	28.6	27.6	17.7	16.3	22.5	21.3	88.4	157.2
October	24.6	23.7	15.2	12.8	19.0	17.3	168.4	65.6
November	18.5	17.2	10.3	10.0	13.7	13.0	269.2	373.0
December	14.5	15.4	5.9	6.3	9.5	10.4	87.4	178.8

structure of trellis system consisted of pre-stressed concrete poles and steel wires and cables. Two strings per plant were annually twined to the top wires, thus allowing hop bines to climb up. The resulting shape was a V-trellis with a top height of 6 m. Three to four selected bines were trained up the strings each year.

The hopyard was organically managed, applying the agronomic strategies reported by [Rossini et al. \(2021\)](#) in a recent review of hop cultivation in the Mediterranean environment. Annually, starting at the end of February 2018, hop crowns and early shoots were pruned to encourage a stronger re-growth and reduce disease incidence ([Turner et al., 2011](#)). For each season, fertilization was performed using a fluid hydrolyzed animal epithelium (8.5% N; 25% C). The liquid fertilizer was supplied at the rate of 200 kg ha⁻¹, which was divided into 10 applications and distributed using the irrigation system. Hopyard also received 2 t ha⁻¹ of pelletized poultry manure (4% N; 4% P₂O₅) applied in autumn prior to hilling up the plant rows. Weeds were mechanically controlled both between and on plant rows. Specifically, from the planting of the hopyard until spring 2018, weeds were controlled by disking along each side of the hop rows, two or three times per season. Starting from April 2018, a permanent naturally occurring flora was left between hop rows, mowing it when necessary. As for the weed control into the hop rows, a first intervention was made by means of crowning

and hilling-up operations in late winter – early spring and, subsequently, using a rotary cultivator for trimmers when required (usually two or three times per season). Copper and sulfur, sprayed as foliar fertilizers, helped also to prevent or limit the spread of fungal diseases. Irrigation was applied as needed using a drip irrigation system.

A reference grid of 40 sampling points, spaced apart 7.5 m × 25 m, was overlaid on the field ([Fig. 1](#)).

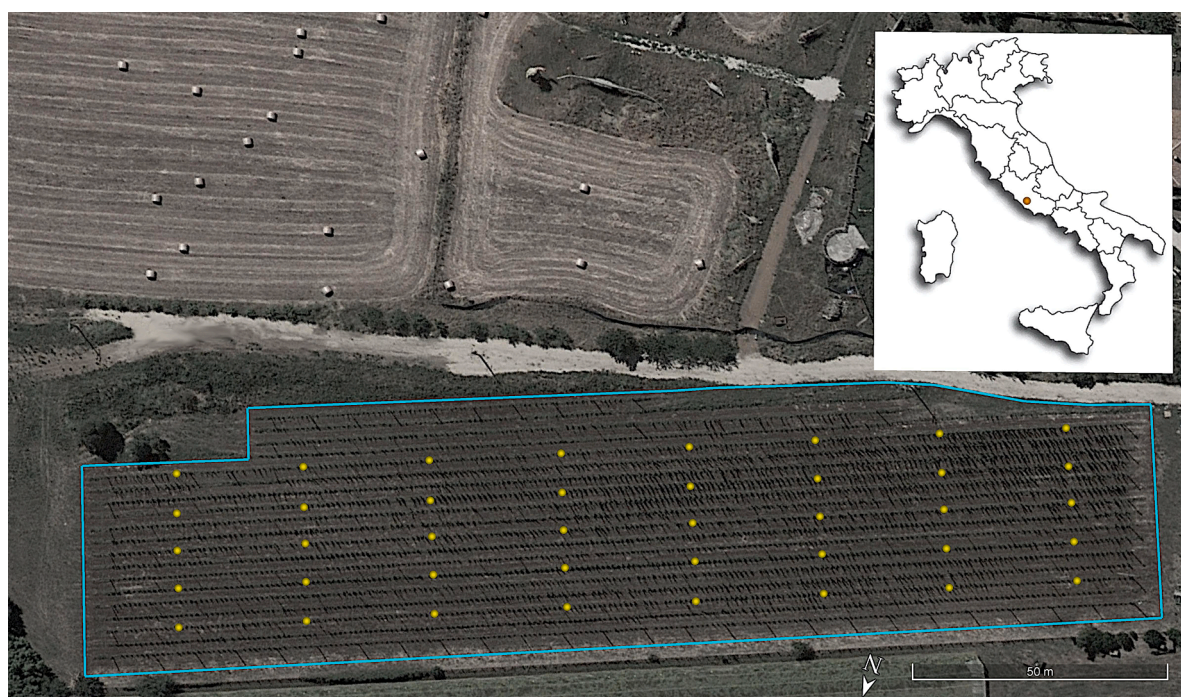
Hop shoot traits (e.g. diameter, length and dry weight) and cone yield were determined during the growing season at the same grid points used for soil sampling.

2.2. Field measurements

At each grid point ([Fig. 1](#)), three cores (5 cm diameter each and 30 cm depth), spaced 15 cm from each other, were collected and mixed. They were used for soil texture analysis in laboratory, using the pipette method ([Bieganski and Ryzak, 2011](#)).

Green shoots were handpicked in each sampling point as soon as bine training was finished (end of May in both years).

Fresh shoots from each plant were cut, counted, measured (length and diameter), and weighed. Then, to determine dry matter yield (reported as kg ha⁻¹), the samples were oven-dried at 55 °C, until constant

**Fig. 1.** Distribution of sampling points across the hopyard.

weight.

Shoot diameter was determined using a digital caliper and taking the measure in the median portion of the shoot. Shoot length was measured by a ruler after surplus shoots were cut at ground level for dry biomass determination.

Cone harvest was performed at ripeness stage (GS: 89): cone closed, lupulin golden, aroma potential fully developed (Rossbauer et al., 1995).

At harvest (end of August – early of September in both years), hop bines were cut in the field and brought to a secondary location to be manually processed.

Picked cones were weighed and then oven-dried at 55 °C until 10% moisture content (marketable moisture).

2.3. Data analysis

Monitoring hop in a privately owned farm allows us to retrieve information on hop growth in actual field conditions, but requires specific agroecological approaches to data analysis, different to those of randomized trials (Fortin and Dale, 2009). To assess the relationships among the hop growth variables and soil texture, data were analyzed independently for each year (2018 and 2019), accounting for the spatial dependence of the sampling points. In addition, the production of cones and shoots of 2018 and 2019 was compared to detect annual differences and provide more insight on the effect of weather variability between different seasons.

As regards the within-year analysis, Dutilleul's modified *t*-test (Clifford et al., 1989; Dutilleul, 1993) was used to explore correlations among variables, while correcting for spatial autocorrelation. Subsequently, generalized least squares regression (glms) was used to quantify the linear dependence between cone and shoot production and correlated variables, as emerged by the Dutilleul's test. Glms regression models both the deterministic and the stochastic component, accounting for the structure of the spatial autocorrelation. For each dependent variable, several models with different correlation structures were tested: a null model with no predictors, a model with no correlation structure (in this case, glms and ordinary least squares regression are equivalent), and glms regressions with linear, exponential, gaussian, spherical and rational correlation structures, using the packages *lm* and *nlme* in R (R Core Team, 2017) and following the procedure indicated in Pinheiro and Bates (2000) and Crawley (2007). Model selection was performed using AIC (Akaike Information Criterion), an index that compares model performance based on a compromise between parsimony and goodness of fit (Akaike, 1974). The model with the lowest AIC (best performance), was selected and presented in the results along with *p*-value and R^2 (Cox and Snell pseudo- R^2 for generalized least squares). As regards the comparison of cone and shoot yield between 2018 and 2019, paired *t*-test was used to consider repeated measurements taken on two different years on the same sampling points, since the hop plant is perennial.

3. Results

Basic information on topsoil texture and production variables of the sampling points are reported in Table 2. Sand was the most variable of

the textural properties, ranging from a minimum of 26.8% to a maximum of 56.0% and having a higher standard deviation (7.1%). The clay content was relatively high (ranging between 26.5% and 53.7%), characterizing the soil as clay loam according to the USDA nomenclature. As for the production variables, shoot number and shoot length slightly increased in 2019, while shoot diameter remained consistent between the two years. Cone and shoot yield increased with the plant age and showed a large variability among sampling points. These results suggested the need for further inferential analysis on seasonal yield differences and on the correlation among the studied variables.

Some relevant information emerged from the explorative analysis of the correlation between soil texture and production variables for 2018 (Table 3) and 2019 (Table 4). The strongest relation was found between cone production and shoot production, with a spatial correlation coefficient of 0.61 for both 2018 and 2019, with *p*-values < 0.01. Another trend suggested by the analysis was a negative relation between production variables (cone yield, shoot yield, shoot number, and shoot length) and clay, which was consistent in both years. The relationship between shoot diameter and clay represented an exception, being positive in sign in both years. However, only in 2018 and for cone yield vs. clay and shoot diameter vs. clay, the spatial correlation coefficients had *p*-values < 0.10. Based upon these exploratory results, the relationships between the most relevant production variables (cone and shoot yield) and clay content were further investigated through model selection.

Simple linear regression with clay as the predictor was the best model (lowest AIC) to represent both the relationship between cone yield and clay (Fig. 2a) and between shoot yield and clay (Fig. 2b), with *p*-values of 0.06 and 0.09 and R^2 of 0.08 and 0.07, respectively. In both cases, the relationships were negative and weak, even though the soil in the yard had a relative high clay content, ranging from 26.5% to 53.7% in the sampling points. Despite the great unexplained variability (low R^2), the trends indicated an average yield reduction of 13 kg ha⁻¹ of cones and 1.68 kg ha⁻¹ of shoots per each additional percentage point of clay (Fig. 2). In contrast, no trend emerged between biomass production variables and clay in 2019 (data not shown).

In both years, the correlation analysis (Table 3 and Table 4) suggested that a positive relation between cone and shoot yield was present. Further analysis provided more insight on that (Fig. 3). A simple linear regression for 2018 and a generalized least square regression for 2019 were selected as the best models to represent the relationship (lowest AIC). The regression models produced low *R*-squared values (R^2 of 0.38 in 2018 and pseudo R^2 of 0.30 in 2019) but significant (*p*-values < 0.001). In both years, cone yield was positively related to shoot yield, with an increase of about 4 kg ha⁻¹ of cones in 2018 and 2 kg ha⁻¹ of cones in 2019 per each additional kg ha⁻¹ of shoots produced. The increase was therefore steeper in 2018 than in 2019.

Comparison of cone and shoot yield between 2018 and 2019 with the *t*-test revealed significant differences between the years in both cases (Fig. 4). Cone yield was lower in 2018 (1.24 t ha⁻¹) than in 2019 (1.44 t ha⁻¹). Similarly, shoot yield was lower in 2018 (197 kg DM ha⁻¹) than in 2019 (218 kg DM ha⁻¹).

4. Discussion

Overall, correlation coefficients between soil texture fractions and

Table 2
Summary statistics of texture and production variables.

	Clay (%)	Sand (%)	Silt (%)	Cone yield (t ha ⁻¹ , 90% DM)		Shoots (No. plant ⁻¹)		Shoot diameter (mm)		Shoot length (cm)		Shoot yield (kg DM ha ⁻¹)	
				2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Mean	36.9	41.6	21.8	1.24	1.44	21.7	21.9	2.3	2.3	78.1	78.6	196.9	218.5
Standard deviation	5.5	7.1	6.3	0.25	0.21	4	3	0.2	0.2	13.2	10.5	35.0	40.4
Minimum	26.5	26.8	7.7	0.76	0.97	12	14	1.9	2.0	48.8	54.8	131.4	142.3
Maximum	53.7	56.0	33.7	1.64	1.88	27	27	2.7	2.6	107.4	102.6	269.3	330.2

Table 3

Correlation coefficients (Duttilleul's *t*-test) of soil and hop growth variables for 2018. Significance levels are: . = *p*-value < 0.10, * = *p*-value < 0.05, ** = *p*-value < 0.01, *** = *p*-value < 0.001.

	Clay	Silt	Sand	Cone yield	Shoot number	Shoot diameter	Shoot length	Shoot yield
Clay	1.00 ***							
Silt	−0.31	1.00 ***						
Sand	−0.54	−0.6	1.00 ***					
Cone yield	−0.29 .	−0.07	0.31	1.00 ***				
Shoot number	−0.25	−0.09	0.25	0.25	1.00 ***			
Shoot diameter	0.38 .	−0.3	−0.09	0.06	−0.21	1.00 ***		
Shoot length	−0.33	−0.32	0.52	0.06	0.19	−0.05	1.00 ***	
Shoot yield	−0.26	−0.32	0.49 .	0.61 ***	0.37 *	0.16	0.25	1.00 ***

Table 4

Correlation coefficients (Duttilleul's *t*-test) of soil and hop growth variables for 2019. Significance levels are: . = *p*-value < 0.10, * = *p*-value < 0.05, ** = *p*-value < 0.01, *** = *p*-value < 0.001.

	Clay	Silt	Sand	Cone yield	Shoot number	Shoot diameter	Shoot length	Shoot yield
Clay	1.00 ***							
Silt	−0.31	1.00 ***						
Sand	−0.54	−0.6	1.00 ***					
Cone yield	−0.41	0.21	0.13	1.00 ***				
Shoot number	−0.22	−0.08	0.22	0.34	1.00 ***			
Shoot diameter	0.37	−0.33	−0.05	−0.2	−0.22	1.00 ***		
Shoot length	−0.34	−0.32	0.53	0.22	0.2	−0.01	1.00 ***	
Shoot yield	−0.05	0.19	−0.13	0.61 **	0.12	−0.2	0.11	1.00 ***

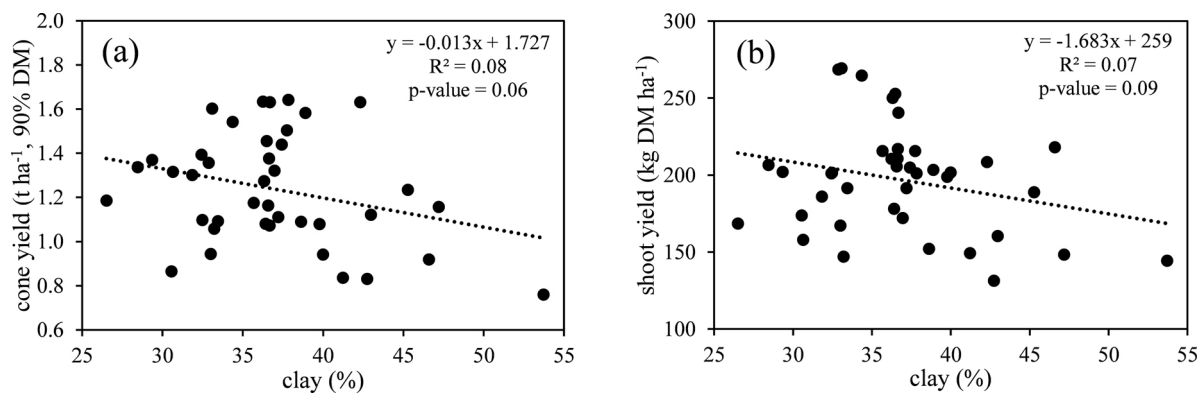


Fig. 2. Relationships between hop production and clay content in 2018 (linear regression): (a) cone yield vs. clay, (b) shoot yield vs. clay.

hop yields were low. This is quite common, since crop performances, under field conditions, are largely influenced not only by the different spatial distribution of soil properties, but also by weather conditions (Usowicz and Lipiec, 2017).

A negative relationship between hop productions and soil clay content was found in both years; conversely, cone yield was positively related to sand content. However, there was not strong evidence that high clay percentages had a detrimental effect on cone and shoot yield. A weak trend arose from correlation analysis only in 2018. From one hand, this confirms that hops grow better in light-textured soils (Neve, 1991); from the other hand, it shows that exceptional weather conditions are needed to make such negative relationship (clay content vs. production) emerge as a trend. Indeed, in 2018 precipitations during hop growing season (approximately from early March to the end of August) were 90% higher than 2019 (497 mm vs. 263 mm, respectively) and 55% higher than the last decade average. Besides the total precipitations over the growing season, it has been suggested that the high-water table during the winter months is the main damaging event for the root system of hops and, consequently, for subsequent growth of the bines (Neve, 1991). In this regard, the heavy rainfalls occurred from January to March 2018 (408 mm), when hops were between dormancy and shoot emergence stage, determined a constantly high soil moisture around the

rootstocks, which probably affected their function and health status. Particularly, from the third decade of February to the second decade of March 2018, we had 21 rainy days that, depending on the clay content of the soil, could have determined a decreased soil aeration and favorable conditions for root and crown rot events. This might have impeded the development of some shoots, weakened growth of the bines, and ultimately reduced hop yield. Afonso et al. (2021a) obtained similar results in Portugal but with a stronger and significant negative relation between clay content and cone yield ($r = -0.666$, $p < 0.01$). This was probably due to the different hopyard management the farmers carried out during the study. The hopyard by Afonso et al. (2021a) was heavily mechanized and frequently irrigated by flooding the field surface. Both these practices, causing soil compaction and an increased bulk density, negatively influence root growth, and movement of air and water through the soil (Keller et al., 2019; Meek et al., 1992; Zeng et al., 2013). Conversely, our hopyard was rarely trafficked by heavy tractors and equipment and was watered by a drip irrigation system. Moreover, hop rows were hilled-up to avoid waterlogging problems near to the superficial feeder roots. These agronomic strategies have lessened the damaging effect of the heavy rainfalls, thus weakening the significance level of the negative relation between soil clay content and hop productions. While clay content was negatively related with all hop production variables, shoot

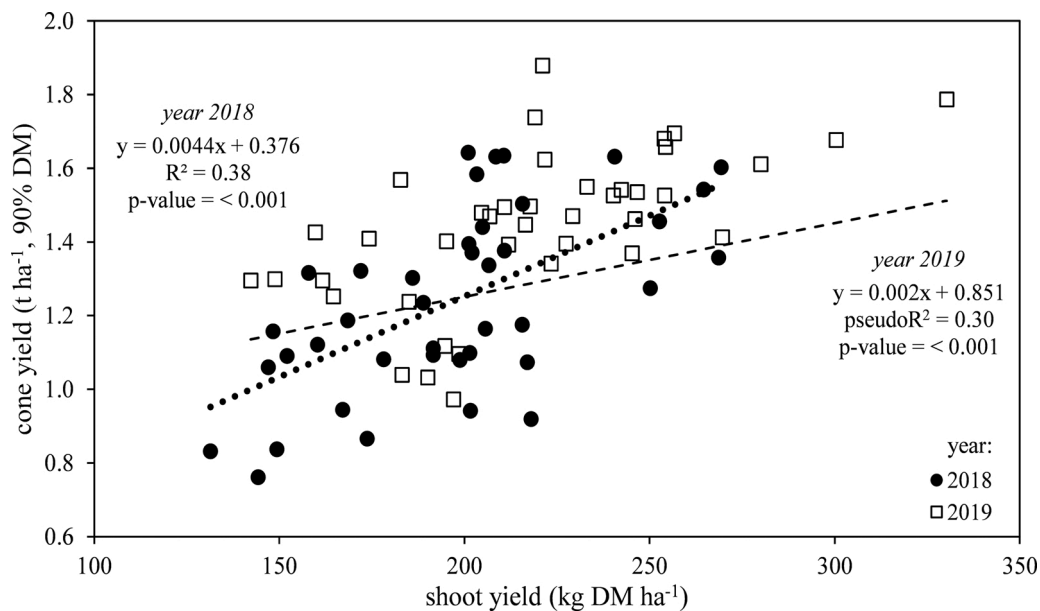


Fig. 3. Relationship between cone yield and shoot yield in 2018 (linear regression) and in 2019 (generalized least squares regression).

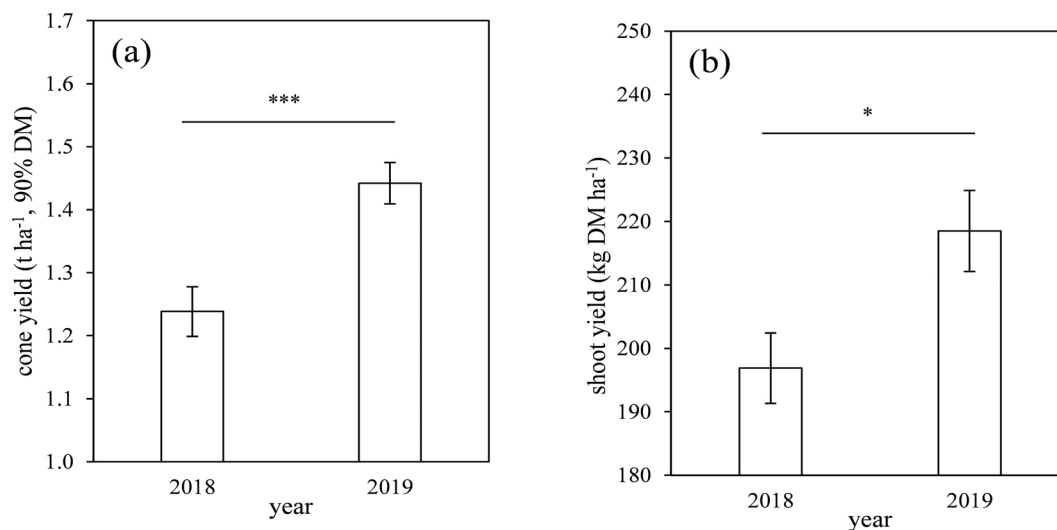


Fig. 4. Hop production in 2018 and 2019 (average and standard error): a) cone yield, b) shoot yield. Results from the paired *t*-test are reported as follow: * = *p*-value < 0.05, ** = *p*-value < 0.01, *** = *p*-value < 0.001.

diameter showed a positive relation with the finest fraction of the soil in both years. This finding can be justified by the negative relation we observed between number of shoots and shoot diameter. Clay content into the soil may have hindered the shoot emergence for the above-mentioned reasons, thus making rootstocks produce fewer but thicker shoots. Likewise, a negative relationship between number and diameter of asparagus spears was also found (Siomos, 2018). Further studies will be needed to disentangle the effect of soil type, soil management, weather course, and hopyard age on cone and shoot yield.

As for the relations between cone yield and shoot traits, the highest positive and significant correlation coefficient in our study was found between shoot yield and cone yield (correlation value = 0.61 in both years). This confirms our hypothesis that the greater the shoot biomass before bine training, the higher will be the cone yield at harvest. Consistently, we previously found the same outcome sampling different hop varieties on experimental plots, in two subsequent seasons (two- and three-years old plants), in Central Italy (Ruggeri et al., 2018).

Both shoot and cone yield significantly increased with hopyard age

(+11% and +16%, respectively). This was expected because plants, in 2018, were still in their establishment phase. However, the differences between the two years might have been exacerbated by the adverse weather conditions of 2018. A similar observation was reported by Rutto et al. (2021) for cultivar trials conducted in Virginia (U.S.A.), where downy mildew, favored by unseasonably high rainfall in 2018, has even led to crop failure. Other studies showed that hop yield is more dependent on weather conditions, genotype and agronomic practices than on plant age, especially when mature plants are sampled (Afonso et al., 2021b; Mozny et al., 2009; Nakawuka et al., 2017; Rossini et al., 2016).

Despite the adverse climatic conditions and considering that the hopyard was organically managed and in its second year of growth, 'Cascade' performed very well in 2018 (1.24 t ha⁻¹ of marketable cones).

If we take into account the 2019 as a more reliable growing season for hop performances, the cone yield we obtained for 'Cascade' in this year (1.44 t ha⁻¹) can be used as term for comparison with other findings. Through an overview of trends of the European hop yields, recently

published by Potopová et al. (2021), it can be noted that the cone yield we found in 2019 was perfectly consistent with the hop yields recorded in the main hop producing countries across Europe. Particularly, Spain, the most important hop producer in the Mediterranean basin, highlighted an historical yield ranging from 0.5 to 2.1 t ha⁻¹, but nearer to 1.5 t ha⁻¹ in the last decade. Additionally, it is worthy of remark that in 2019 the hopyard was not yet in its full production capacity, which, according to Sirrine et al. (2014), usually starts from the fourth year for cultivar 'Cascade'.

When we compare plants of cultivar 'Cascade' having the same age, shoot number per plant we found in this study was lower (−24%, on average) than that we observed at experimental-plot scale (Ruggeri et al., 2018). Conversely, shoot diameter was found to increase by 40% moving from plot to hopyard scale study, but plants were not equal in age (Rossini et al., 2020).

Shoot yield gained in this study is not comparable with previous findings because here we determined the weight of the entire shoot, while the other studies reported the marketable yield (the tender part of the shoot).

5. Conclusions

This study represents the first attempt to assess the yield potential of an organic commercial hopyard during its establishment period. Even though the experiment is rather small if compared to those conducted in countries where hop is traditionally grown (generally, more than 300 plants sampled per plot), it is the biggest one among those conducted in the new growing areas of the Mediterranean environment (typically from 3 to 6 plants sampled per plot). The farm size in the southern Europe is markedly smaller than that of northern counterparts, but it is appropriate for the available resources, technical means and local hop market needs.

Spatialized data gathered in this study, proved 'Cascade' to be a hop cultivar very well adapted to the Mediterranean region. It yielded more than 1 t ha⁻¹ of marketed cones since its second year, despite the adverse weather occurred in 2018, even under organic management conditions. This allows farmers to begin the recovery of the establishment costs from the second year after planting. Currently, organic farming is practically unavoidable in the new growing areas because chemicals are not registered yet for the use on hops. In the future, the choice between the two farming regimes should be accurately evaluated according to the availability of new plant protection products, cone prices and raw material costs.

The negative relationship we found between soil clay content and hop production evidenced that hops prefer light-textured soils than heavy soils. However, the weakness of such relationship, and the increasing yields we obtained in two consecutive harvests, suggested that the cultivation on clay loam soils is feasible, applying the proper agronomic strategies (e.g., hilling up the rows and using a drip irrigation system).

Since shoot production before bine training was found to be positively and strongly related to cone yield in both years, green shoot yield in spring could be used as a predictor of hop harvest.

Despite the challenges of their cultivation in a new growing area, hops can represent the key crop for the differentiation strategy of local craft breweries.

CRedit authorship contribution statement

Roberto Ruggeri: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Massimo Tolomio:** Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Massimo Muganu:** Writing – review & editing. **Paolo Loreti:** Investigation, Writing – review & editing. **Giuseppe Virga:** Writing – review & editing. **Nicolò Iacuzzi:** Writing – review & editing. **Francesco Rossini:**

Conceptualization, Data curation, Supervision, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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