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Hop (*Humulus lupulus* L.): Suitability of Traditional Cultivars to a Low-Trellis Farming System in a Semiarid Environment

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***Abstract.* *Humulus lupulus* is a dioecious twining herb, with an outstanding vertical development capacity. Hop plants are usually grown on trellises up to 4.5 to 6.0 m high, whose management requires intense use of water, fertilizers, pesticides, and labor. In semiarid Mediterranean areas, where native resources are often scarce, the adoption of low-trellis farming systems could be a sustainable option for hop cultivation. With the aim of evaluating hop suitability to low-trellis cultivation in a Mediterranean environment, in 2018 and 2019 three traditional hop genotypes (‘Cascade’, ‘Chinook’, and ‘Nugget’) were grown, and their development rate was evaluated and put in relation with the plants’ cone, root, and biomass yield. Moreover, organic (fragmented pine bark) and synthetic [black polyethylene (PE) plastic film] mulches were applied on the same cultivars, and both epigeal and hypogeal development were evaluated. The results showed that the faster the growth in the first two phases of plant elongation (up to 50% of the height of the upper wire), the lower the yield in both cones and total epigeal biomass. A fast growth rate was instead associated with a higher hypogeal biomass production. Mulching was able to significantly affect the hypogeal biomass, specifically for cv. Cascade, where the use of synthetic mulching allowed significant root biomass increases. The analysis of the results obtained showed that hop’s suitability to a low-trellis farming system is highly variable among varieties in the semiarid Mediterranean environment.**

In northern Italy, hops grow as spontaneous species (Mongelli et al., 2015), and those environments are thought to be the most suitable for hop cultivation. However, several preliminary studies have successfully explored the possibility of introducing this crop to semiarid Mediterranean environments (Forteschi et al., 2019; Marceddu et al., 2020; Rossini et al., 2016, 2021). Several genotypes have been selected that are best adapted to the local growth conditions (Rossini et al., 2016). Recent studies have also been carried out to assess the response of hops in terms of crop productivity and cone quality. A survey conducted by Rossini et al. (2016) has shown that some varieties obtained higher yields, justifying the spread of varietal groups that, although heterogeneous, guarantee sustainability of hop cultivation.

From a qualitative point of view, both panel tests (Marceddu et al., 2020; Rossini et al., 2016) and laboratory analyses (Forteschi et al., 2019) demonstrated the excellent potential of hop production obtained in the Mediterranean environment.

However, high investment costs, and time-consuming and resource-consuming crop management, are major constraints to a wider expansion of hops in Mediterranean areas. Traditional hop cultivations usually adopt climbing supports up to 4.5 to 6.0 m high, where plants are allowed to grow up until harvest, forming a dense vegetation wall. In these conditions, demand for water and fertilizer, pest and disease control, and harvest management are outstanding. Hence, many experiments have been conducted to explore the feasibility of growing hops on reduced 2- to 3-m climbing structures (“low trellis”), with many advantages related to easier crop management, lower initial expenses, and enhanced sustainability. Several studies have shown that low-trellis hop farming systems offer benefits related to environmental protection, because phytosanitary treatments can be carried out more efficiently and with less dispersion because of reduced vertical development (Beatson et al., 2009; Darby, 2005). The cultivation of hops on lower trellises also allows a more effective biological control of major pests and diseases (Darby, 2004; Gunn and Darby, 1987; Lilley et al., 1999). A few dwarf varieties have been selected to fit these reduced production systems, but significant research is also addressed to evaluate the performances of traditional hop varieties under those constrained conditions.

With the aim to evaluate the yield and growth rate of hops in a low-trellis system in a Mediterranean environment, three American hop varieties (Chinook, Nugget, and Cascade) were compared in 2018 and 2019, with or without the application of two mulches (organic and synthetic). The progression of plants’ climbing on the vertical supports was monitored by reference to the phenological development scale pointed out for hop (Rossbauer et al., 1995). Furthermore, hypogeal and epigeal biomass were measured and compared in all treatments.

Materials and Methods

Experimental site. The experiment was carried out in 2018 and 2019 at the University of Palermo, Department of Agricultural, Food and Forest Sciences (D/SAAF) “Orleans” farm (Palermo, Italy, 38°060 2700 N; 13°210 0100 E; 22 m a.s.l.). In both years, climatic patterns (Fig. 1) during the cultivation periods were characterized by scarce rainfall and high summer temperatures (maximum values >30 °C).

Plant management. For research purposes, a single hop row was built, with 2.5-m-high iron poles supporting structures; horizontal iron wires run at the top of the poles, and coconut fiber ropes provided vertical supports, onto which the plants were allowed to climb. All plants were purchased from a nursery in northern Italy. Five plants for each variety (Cascade, Chinook, and Nugget) at the development stage of four to six true leaf development stage (≈10 cm high), were used for the trial. In both years, each plant was placed in a 40-L pot, filled with a brown peat and perlite (3:2) mixed substrate, with a deep draining layer composed of expanded clay and gravel (1:1). In each variety, a mulch-free control, a synthetic mulch treatment (black PE film), and an organic mulch treatment (pine bark) were compared. Synthetic mulching used a 1-mm-thick black PE plastic film; organic mulching was covered with a 5-cm layer of fragmented pine bark (diameter 10–20 mm).

The experiments started on 9 Apr 2018, and 6 May 2019, in the first and in the second year, respectively. In both years, a supporting mineral fertilization was applied to plants (50 g per plant) using a ternary fertilizer (15N–7.3P–21.3K), also containing microelements (Mg, Fe, and B, at amounts of 2%, 0.1%, and 0.01%, respectively). A localized irrigation system was set up with a single dripline along the row. The irrigation system was equipped with a closing valve and a pressure gauge to control the water pressure and flow rate needed for the crop requirements. Frequent irrigation cycles at low volumes were adopted to ensure available water amounts close to field capacity.

The harvest period was assessed through the evaluation of the cones’ dry matter content. Cones were harvested once they reached a 20% dry matter value (Calderwood and Post, 2015). At harvest time, the total biomass obtained for each plant was weighed, and sorted by marketable (hop cones) and unmarketable biomass (annual stems and leaves). In addition,

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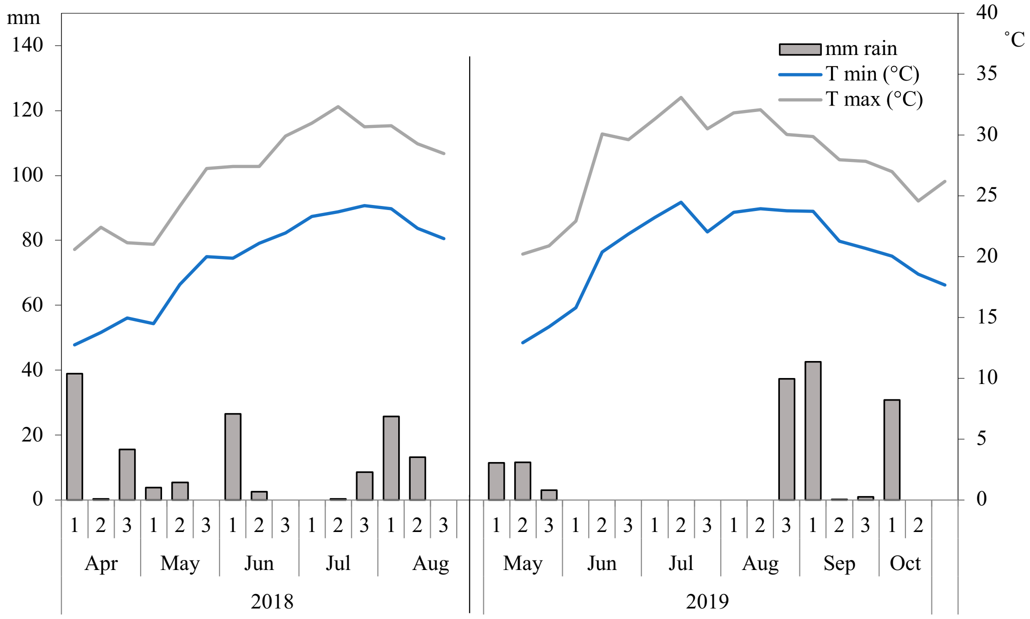

Fig. 1. Ten-day values of rainfall and temperatures recorded at the "Orleans" farm during the 2018 and 2019 growing seasons (Palermo, PA, Italy).

in both years of experimentation (2018 and 2019), during the dormancy of rhizomes, the total root biomass was weighed after both growing seasons.

Calculation of hop growth rate and growing degree days. In each year, hop plants were periodically checked to monitor their phytosanitary and developmental conditions. The main phenological phases were assessed using the BBCH (Biologische Bundesanstalt, Bundessortenamt and CHemical industry) scale (Rossbauer et al., 1995). Vertical development of the crop was monitored at stage 3 ("Elongation of bines") of the BBCH scale twice per week and expressed as a percentage of top wire height (2.50 m).

Growing degree days (GDDs; °C) were calculated starting on the day of transplant, corresponding to the BBCH phase 1.2 (second pair of leaves unfolded). The GDDs accumulated when plants had reached the threshold height values of 62.5 cm, 125.0 cm, 187.5 cm, and 250.0 cm (corresponding to 25%, 50%, 75%, and 100% of wire length) were recorded. All calculations were performed according to the general formula:

$$\mathrm{GDD} = \sum\nolimits_{i=1}^{k} (\mathrm{T}_{\mathrm{avg}} - \mathrm{T}_{\mathrm{base}})_{\mathrm{i}},$$

where i and k indicate the starting and ending date of each growth stage (i.e., first and last days of measurement, respectively), $\mathrm{T}_{\mathrm{avg}}$ is daily average temperature, and $\mathrm{T}_{\mathrm{base}}$ is base temperature (i.e., temperature value below which plant growth is assumed to be zero).

$\mathrm{T}_{\mathrm{avg}}$ was calculated based on daily temperature measurements, as follows:

$$\mathrm{T}_{\mathrm{avg}} = \frac{(\mathrm{T}_{\max} + \mathrm{T}_{\min})}{2},$$

where $\mathrm{T}_{\min}$ is the minimum day temperature; when $\mathrm{T}_{\min} < \mathrm{T}_{\mathrm{base}}$, then $\mathrm{T}_{\mathrm{base}}$ should be used for calculation. This, however, never happened in either trial season, occurring in late spring and summer. $\mathrm{T}_{\max}$ is the maximum day temperature.

In the choice of the base temperature ($\mathrm{T}_{\mathrm{base}}$), reference was made to the evidence shown in a recent work. To accurately calculate the GDDs for hops in a Mediterranean environment, Marceddu et al. (2020) discussed the idea of differentiating the $\mathrm{T}_{\mathrm{base}}$ based on the phenological crop phases; a $\mathrm{T}_{\mathrm{base}} = 0\,^{\circ}\mathrm{C}$ was found more suitable in the vegetative phases, whereas, after the phase BBCH 2.1, the adoption of base temperatures of 5 °C (as proposed by Srečec et al., 2008) or 10 °C were substantially the same.

In the two trial years, all hop plants reached the maximum height during the vegetative phases (between BBCH 1.2 and 2.1). Thus, following the results obtained in a previous work (Marceddu et al., 2020), it was opted for a calculation of GDDs through the adoption of 0 °C as base temperature ($\mathrm{T}_{\mathrm{base}}$).

Hop Growth Rates (HGRs) were calculated according to the following formula:

$$\mathrm{HGR} = \mathrm{H}_{\mathrm{t}} / \sum_{i=1}^{k} \mathrm{GDD},$$

where H_{t} is the height value reached on the wire by the plants in cultivation, and the $\sum_{i=1}^{k} GDD$ represents the corresponding thermal sum necessary to reach the same height, with i and k representing the starting and ending date of each vertical growth interval. Similar to GDDs, HGRs were calculated for the whole duration of the plants' elongation on ropes ($\mathrm{HGR}_{\mathrm{tot}}$), as well as for the four stages (0% to 25%, 25% to 50%, 50% to 75%, and 75% to 100%) to obtain the partial values termed $\mathrm{HGR}_{0\text{–}25}$, $\mathrm{HGR}_{25\text{–}50}$, $\mathrm{HGR}_{50\text{–}75}$, and $\mathrm{HGR}_{75\text{–}100}$, respectively.

Statistical analysis. All data collected were submitted to analysis of variance (ANOVA) using the statistical software Minitab (version 19.2.0.0). The general linear model procedure was used, setting as the dependent variable the measured durations (in days) of plants' elongation stages on the trellis, the corresponding GDD values (in °C), the calculated values of HGRs (cm/GDD), and all the measured plant traits in grams of DM (g DM) (hypogeal biomass, cone yield, and total epigeal biomass). The factors "year" (Y) (2018 and 2019), "variety" (V) (Cascade, Chinook, and Nugget), and "mulching treatment" (M) (organic, synthetic, and no mulch) were set as independent variables. When the ANOVA offered statistically significant results, the differences between mean values were appreciated through the Tukey's test ($P \leq 0.05$); no post hoc test was performed on the main effects, when the corresponding interactions proved to be significant ($P \leq 0.05$) at the ANOVA (Gomez and Gomez, 1984). To assess any significant association within the measured data, Pearson's correlation coefficients were calculated on pooled data between cone yields, plant biomass (hypogeal and epigeal), and HGR parameters.

Results

The duration of plants' elongation [days (dd) from transplant to achievement of maximum height, i.e., 2.50 m] was different between the two years, as plants reached, on average, the maximum height in ≈83 d in 2018 and 57 in 2019 (Table 1). Throughout the same time span, also GDDs accumulation (°C) was higher in 2018 (1753.4 GDD) than in 2019 (1263.3 GDD). Consequently, HGR was higher in 2019 than in 2018, because in the first trial year, plants gained ≈0.14 cm per each cumulated temperature degree, whereas plant growth was much faster (≈0.2 cm/GDD) in 2019. In the first year, more than 70% of the time requested for full elongation was occupied by the first half of climbing (up to 50% of top wire height), whereas in 2019 the same substage lasted

≈50% of total duration. Significant differences show up, in fact, between the values of dd_{0-25} and GDD_{0-25}, by one side, and dd_{25-50} and GDD_{25-50}, by the other, measured in the two years (Table 1).

On average, irrespective of year and genotype, plant elongation on ropes was initially slow, and faster in the second half of climbing. The cv. Chinook had the fastest growth rate (Table 1), reaching the maximum height on the trellis in ≈61 d (i.e., 2 weeks before the other two varieties). The cv. Chinook had, in fact, the highest HGR values in all growth substages. This difference among varieties resulted in statistically significant HGR_{50-75} (Table 1). In the earlier observations, however, a significant Y × V interaction showed up, demonstrating the different behavior of genotypes across years (Fig. 2A and B). Hence, in both years the cv. Chinook took approximately the same number of days to complete the first growth substage (0% to 25%), showing a high HGR value, whereas the other two varieties exhibited contrasting responses between years.

The mulching treatments (Table 1) did not show any significant effect on plant growth parameters calculated on the whole growth period, otherwise showing an influence on plants' growth rates in the first time span of plants' elongation (0% to 25%), with the synthetic mulch able to trigger a significantly faster growth of plants (25.3 dd), whereas the organic mulching seemed to slow down plant growth (35.5 dd). In the following substages, although the effect of mulching was always detectable, the differences between treatments were as small, as they could not be appreciated by the statistical analysis.

The yield of cones (Table 2) was affected by the year, which acted in association with both the genotypes and the mulching treatment (interactions Y × V and Y × M, significant at $P \leq 0.05$). In both years, the cv. Chinook allowed the highest yields, i.e., 49.3 g DM per plant in 2018, and 40.5 in 2019, and the cv. Nugget the lowest (less than 20 g DM per plant in both years), whereas the cv. Cascade exhibited a strong differentiation between years, expressing yields ranking among the highest in 2018 and among the lowest in 2019 (Fig. 3A). The observation of treatments showed, instead, the high reactivity of hop plants to the synthetic mulch, which allowed higher yields in 2018 and lower in 2019, whereas the other two treatments gained statistically no different yield values, independently of year.

Plant aerial biomass (Fig. 4) was the highest in the 'Chinook', followed by 'Cascade' and 'Nugget', respectively. Within each variety, no significant effect of the mulching treatment could be enlightened by the statistical analysis, and the significant V × M interaction (Table 2) can be evidenced between the highest ('Chinook' with organic mulch, 197.5 g DM per plant) and the lowest biomass values ('Nugget' with organic mulch, 92.1 g DM per plant). On average, no difference was detectable on the effect of mulching treatments.

The hypogeal biomass turned out significantly different ($P \leq 0.05$) between 2018 and 2019. The ANOVA also showed a significant

Table 1. Mean values of durations (days), thermal sums [growing degree days (GDDs)], and hop growth rates (HGRs) (cm/GDD) of plant elongation on a 2.50-m wire, in four intervals of hop climbing (up to 25%, 25% to 50%, 50% to 75%, 75% to 100% of top wire height, and total –0% to 100%) of three hop varieties (Cascade, Chinook, and Nugget) cultivated in 2 years (2018–19) under two mulching treatments (synthetic and organic) and without mulching (no mulch). Mean values of main effects (year, variety, and mulching treatment) and results of analysis of variance (*P* values) for main effects and first-order interactions. For each group of means, values followed by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test). For interactions, significant *P* values ($P \leq 0.05$) are marked in bold.

	Percentage intervals of top wire ht														
	Total (0 to 100)			0–25			25–50			50–75			75–100		
Source	dd	GDD (°C)	HGR (cm/ GDD)	dd	GDD (°C)	HGR (cm/ GDD)	dd	GDD (°C)	HGR (cm/ GDD)	dd	GDD (°C)	HGR (cm/ GDD)	dd	GDD (°C)	HGR (cm/ GDD)
Year (Y)															
2018	83.3 a	1753.4 a	0.14 b	38.5	715.7	0.09 b	23.7 a	516.9 a	0.14 b	11.0	265.6	0.26	10.1	255.1	0.27 a
2019	57.3 b	1263.3 b	0.20 a	21.5	413.4	0.14 a	11.3 b	219.7 b	0.31 a	10.3	264.8	0.34	14.2	365.4	0.20 b
Significance of F test (P value)	*0.000*	*0.002*	*0.001*	*0.000*	*0.001*	*0.002*	*0.000*	*0.000*	*0.000*	*0.902*	*0.834*	*0.122*	*0.073*	*0.117*	*0.020*
Variety (V)															
Cascade	75.7 ab	1624.5	0.16	31.6	584.5	0.12	17.9	387.0	0.22	14.3	360.0	0.25 b	11.9	293.0	0.23
Chinook	61.1 b	1284.7	0.19	24.9	476.1	0.13	19.3	382.9	0.21	7.6	183.7	0.37 a	9.3	241.9	0.27
Nugget	76.0 a	1651.9	0.16	34.6	650.2	0.10	15.9	351.7	0.23	10.4	261.4	0.27 b	15.1	388.6	0.20
Significance of F test (P value)	*0.042*	*0.056*	*0.124*	*0.051*	*0.123*	*0.203*	*0.297*	*0.420*	*0.480*	*0.182*	*0.230*	*0.009*	*0.055*	*0.07*	*0.057*
Mulching treatment (M)															
No mulch	76.6	1649.0	0.16	29.8 ab	553.0 ab	0.11 ab	23.0	493.7	0.21	10.8	271.7	0.28	13.0	330.6	0.22
Synthetic	64.5	1352.5	0.19	25.3 b	469.3 b	0.14 a	16.2	322.2	0.23	10.2	241.6	0.28	12.8	319.4	0.23
Organic	74.6	1625.9	0.16	35.5 a	677.3 a	0.09 b	17.0	374.5	0.21	11.1	286.1	0.32	11.0	288.0	0.25
Significance of F test (P value)	*0.188*	*0.179*	*0.136*	*0.012*	*0.018*	*0.013*	*0.869*	*0.607*	*0.505*	*0.805*	*0.769*	*0.455*	*0.559*	*0.791*	*0.520*
Significance of *F* test (*P* value) for interactions															
Y × V	*0.397*	*0.354*	*0.585*	***0.001***	***0.002***	***0.001***	*0.515*	*0.347*	*0.196*	*0.221*	*0.293*	*0.167*	*0.317*	*0.548*	*0.911*
Y × M	*0.464*	*0.389*	*0.581*	*0.253*	*0.347*	*0.553*	***0.030***	***0.024***	*0.057*	*0.582*	*0.623*	*0.932*	*0.794*	*0.696*	*0.223*
V × M	*0.396*	*0.347*	*0.417*	*0.597*	*0.725*	*0.250*	*0.106*	*0.096*	*0.746*	*0.542*	*0.564*	*0.303*	*0.625*	*0.505*	*0.219*

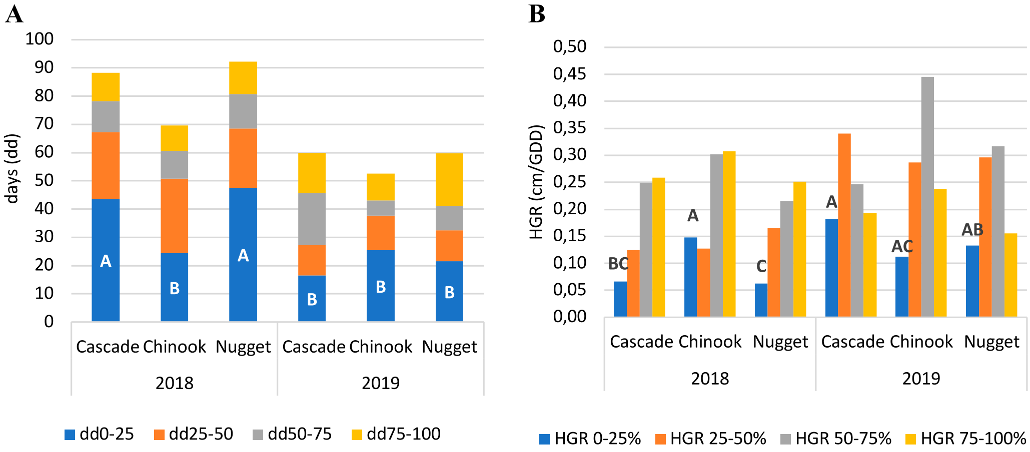

Fig. 2. Cumulated durations (**A**; days) and corresponding hop growth rate (HGR) values [**B**; cm/growing degree days (GDD)] calculated for subsequent intervals of plants' elongation (up to 25%, 25% to 50%, 50% to 75%, 75% to 100% of top wire height) in a 2-year cultivation trial of three hop varieties (Chinook, Cascade, and Nugget) at "Orleans" farm (Palermo, PA, Italy). Mean values of the interaction "year" × "variety." For each group of means, bars marked by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test).

($P \leq 0.05$) V × M interaction (Table 2; Fig. 5), assessing a different response of genotypes to the mulching treatments. In fact, the adoption of synthetic mulching was a valuable instrument to positively enhance the root biomass yields for the cv. Cascade, different from what was found in the cv. Nugget, for which it showed to have a downward effect. Under both treatments (organic and synthetic mulch), as well as in the control, 'Chinook' emerged as having the best capability to accumulate hypogeal biomass, which averaged weight values significantly higher than the other two varieties (Fig. 5).

The analysis of correlations (Table 3) showed, at first instance, a strong and direct association (r = 0.695) between dry cone yield and dry epigeal biomass. These two characters did not evidence, on the other hand, any significant association with total growth duration and HGR. Otherwise, the biomass and cone yield of both plant demonstrated a close inverse association with HGR in the interval 25% to 50% of top wire height (r = −0.579, and r = −0.435, respectively). As expected, the same parameters demonstrated a direct association with the inverse measured values, that is, the duration (in days) of the corresponding plants' growth intervals. Cone yield showed, additionally, a significant inverse association with the duration of the final elongation stage of plants (75% to 100% of total wire height; r = −0.395).

Otherwise, a significant inverse relationship (r = −0.518) showed up between total cycle duration and hypogeal biomass; consequently, the hypogeal biomass resulted positively associated (r = 0.526) with HGR_{tot}. As shown, each partial HGR value demonstrated a positive association with hypogeal biomass values, whereas the corresponding partial durations (dd_{0-25} to dd_{75-100}) always exhibited negative r values. Finally, all partial HGRs, as well as total HGR (from the beginning of trial to complete elongation on wire), demonstrated a close inverse correlation (r values always <0) with their corresponding stage duration (in days). Total duration of the plants' elongation was directly correlated with the first three stages, with decreasing r values, showing that the initial elongation stage is the most relevant part of total number of days.

Table 2. Mean values of yield of cones per plant (g DM), epigeal and hypogeal plant biomass (g DM), of three hop varieties (Cascade, Chinook, Nugget) cultivated in 2018 and 2019 at "Orleans" farm (Palermo, Italy), under two mulching treatments (synthetic and organic) and without mulching (no mulch). For each group of means, values followed by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test). For interactions, significant P values ($P \leq 0.05$) are marked in bold.

	Cone yield (g DM)	Epigeal biomass (g DM)	Hypogeal biomass (g DM)
Year (Y)			
2018	38.4	177.4 a	240.30 b
2019	27.2	113.1 b	276.35 a
Significance of F test (P value)	*0.006*	*0.000*	*0.007*
Variety (V)			
Cascade	34.6	139.8	253.38
Chinook	44.9	184.5	321.62
Nugget	19.7	111.5	199.98
Significance of F test (P value)	*0.000*	*0.001*	*0.000*
Mulching treatment (M)			
No mulch	30.7	150.2	303.68
Synthetic	36.9	148.2	248.73
Organic	30.1	139.8	250.71
Significance of F test (P value)	*0.080*	*0.697*	*0.034*
Significance of *F* test (*P* value) for interactions			
Y × V	***0.012***	*0.981*	*0.794*
Y × M	***0.042***	*0.175*	*0.933*
V × M	*0.067*	***0.015***	***0.003***

Discussion and Conclusions

Significant variability was assessed in measured cone and biomass yields, according to the genotype and the treatments, but also dependent on year. This is not surprising in Mediterranean environments, where, even when irrigation is applied, climatic variability often results in wide yield oscillations (Arnon, 1992). Hence, regardless of the variety and the mulching treatment applied, in 2018, hop plants found more favorable climatic conditions, positively affecting both yields and plant growth rates.

The observed data also showed that the cultivar Chinook proved to be more stable, with significantly higher and constant production levels in both growing seasons. Oppositely, the cv. Cascade exhibited a higher reactivity to interannual variability, showing the best yield performance in the most favorable year, and dramatically lower productions in the second trial year. A better performance of the 'Chinook' variety compared with the other genotypes also emerged in a previous work (Marceddu et al., 2020), where this behavior was supposedly based on the higher precocity of this genotype. In this experiment also, the cv. Chinook was the earliest variety, with a remarkable homogeneity of growth rate between the 2 years.

The adoption of a low-trellis farming system could have played a significant role in this outcome, due to physiological imbalances eventually linked to the poor suitability of 'Cascade' and 'Nugget' to this constraining management. Although all three varieties are widely grown all around the world (Darby et al., 2017;

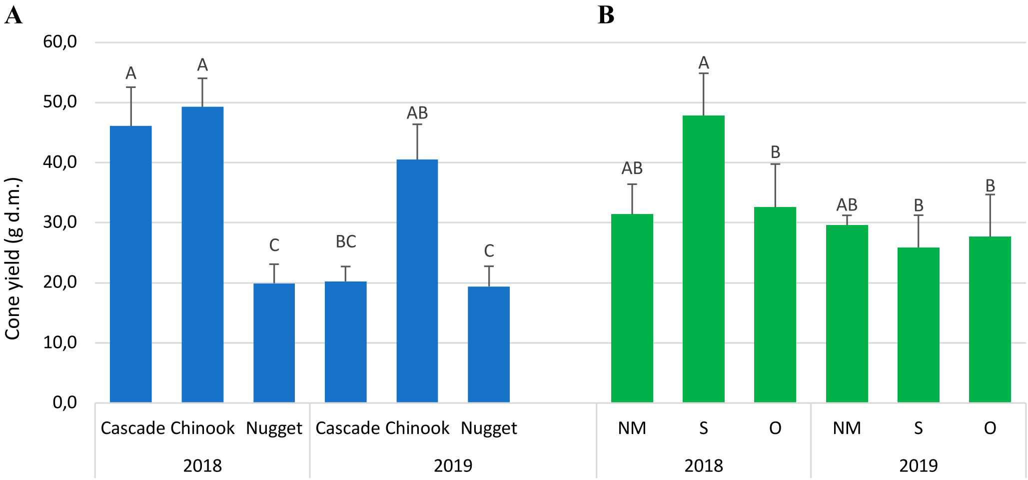

Fig. 3. (**A**) Cone yield (g of DM) obtained in a 2-year cultivation trial of three hop varieties at "Orleans" farm (Palermo, PA, Italy); (**B**) mean values + SEM of the interactions "year" × "variety" (**A**) and "year" × "mulching treatment" (**B**). For each group of means, bars marked by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test). NM = no mulch; S = synthetic; O = organic.

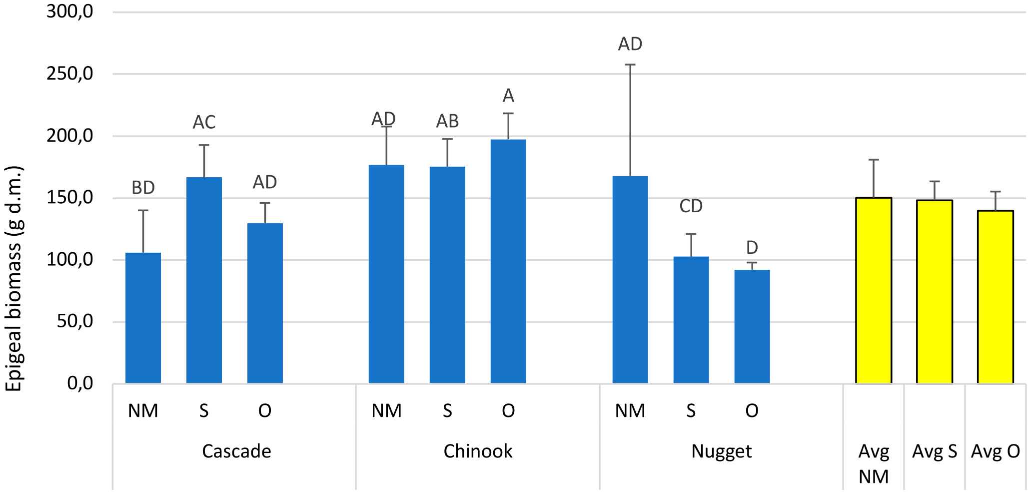

Fig. 4. Plant epigeal biomass (g of DM) obtained in a 2-year cultivation trial of three hop varieties at "Orleans" farm (Palermo, PA, Italy). Mean values + SEM of the interaction "variety" × "mulching treatment," and mean values of the mulching treatments. Bars marked by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test). NM = no mulch; S = synthetic; O = organic.

Dodds, 2017), it appears that these two genotypes did not meet the best conditions to express their full yield potential.

The measured values of hypogeal biomass production also allowed some interesting considerations. In perennial crops such as hop, the storage capacity in root biomass, although not directly associated with yield, takes a special relevance. In this respect, our work demonstrated

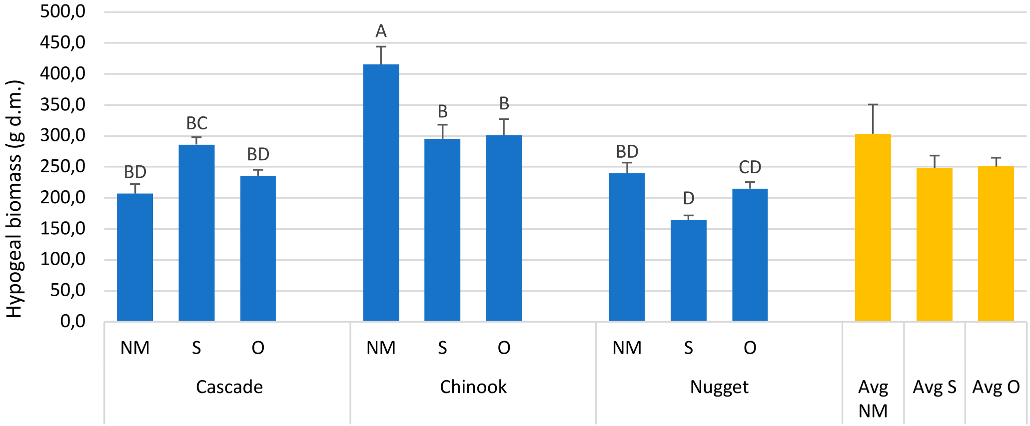

Fig. 5. Plant hypogeal biomass (g of DM) obtained in a 2-year cultivation trial of three hop varieties at "Orleans" farm (Palermo, PA, Italy). Mean values + SEM of the interaction "variety" × "mulching treatment," and mean values of the mulching treatments. Bars marked by the same letter are not significantly different at $P \leq 0.05$ (Tukey's test). NM = no mulch; S = synthetic; O = organic.

Table 3. Pearson's correlation coefficients and corresponding *P* values (in italic) between dry plant weight (g DM), root/rhizome system biomass (g DM), cone yield (g DM), and hop growth parameters [hop growth rate (HGR) and duration of elongation stages in four intervals of hop climbing on wire] in a 2-year cultivation trial of three hop varieties at "Orleans" farm (Palermo, PA, Italy). Significant *P* values (<0.05) are marked in bold.

	Epigeal biomass (g DM)	Hypogeal biomass (g DM)	HGR_{0-25}	HGR_{25-50}	HGR_{50-75}	HGR_{75-100}	$\mathrm{HGR}_{\mathrm{tot}}$	dd_{0-25}	dd_{25-50}	dd_{50-75}	dd_{75-100}	$\mathrm{dd}_{\mathrm{tot}}$
Cone yield	0.695	0.334	−0.017	−0.435	0.112	0.342	−0.018	0.007	0.370	−0.205	−0.395	−0.016
(g DM)	***0.000***	*0.077*	*0.928*	***0.018***	*0.562*	*0.069*	*0.926*	*0.973*	***0.049***	*0.286*	***0.034***	*0.934*
Epigeal biomass	–	0.336	−0.111	−0.579	−0.071	0.281	−0.247	0.198	0.614	−0.074	−0.309	0.311
(g DM)		*0.075*	*0.565*	***0.001***	*0.715*	*0.140*	*0.196*	*0.303*	***0.000***	*0.705*	*0.103*	*0.101*
Hypogeal biomass		–	0.360	0.242	0.532	0.205	0.526	−0.429	−0.074	−0.231	−0.303	−0.518
(g DM)			*0.055*	*0.206*	***0.003***	*0.286*	***0.003***	***0.020***	*0.705*	*0.228*	*0.110*	***0.004***
HGR_{0-25}			–	0.349	0.05	−0.052	0.692	−0.880	−0.175	0.108	0.073	−0.649
				0.064	*0.798*	*0.787*	***0.000***	***0.000***	*0.365*	*0.578*	*0.707*	***0.000***
HGR_{25-50}				–	0.312	−0.398	0.625	−0.440	−0.868	−0.057	0.324	−0.650
					0.099	***0.033***	***0.000***	***0.017***	***0.000***	*0.770*	*0.087*	***0.000***
HGR_{50-75}					–	0.115	0.640	−0.258	−0.274	−0.750	−0.274	−0.689
						0.553	***0.000***	*0.177*	*0.151*	***0.000***	*0.150*	***0.000***
HGR_{75-100}						–	0.066	0.169	0.358	−0.170	−0.859	−0.017
							0.733	*0.381*	*0.056*	*0.378*	***0.000***	*0.931*
$\mathrm{HGR}_{\mathrm{tot}}$							–	−0.734	−0.483	−0.440	−0.140	−0.965
								0.000	***0.008***	***0.017***	*0.469*	***0.000***
dd_{0-25}								–	0.231	−0.034	−0.185	0.760
									0.228	*0.860*	*0.337*	***0.000***
dd_{25-50}									–	0.044	−0.317	0.557
										0.820	*0.094*	***0.002***
dd_{50-75}										–	0.169	0.446
											0.380	***0.015***
dd_{75-100}											–	0.062
												0.748

that, opposite to what emerged for plant epigeal biomass and cone yield, a fast growth rate (as expressed by HGR values) was associated with a higher hypogeal biomass production. Mulching treatments had a crucial importance in this sense. The effect exerted by mulching treatments was strongly dependent on genotype: as shown, the use of synthetic mulching allowed significant hypogeal biomass increases in the cv. Cascade, but not in the other genotypes. A strong effect of mulches on soil temperature is widely acknowledged by the literature, and enhanced maximum and minimum temperatures are generally attributed to PE mulches (Bristow, 1988; Gu et al., 2019), whereas a lowering effect is recognized for organic mulches (Subrahmaniyan and Zhou, 2008; Yordanova, 2017). This remarkable thermal effect can justify the high HGR value recorded for synthetic mulching treatment in the first time span of plant elongation (0% to 25%), significantly higher than that relative to organic mulched and unmulched pots. Hence, synthetic mulch made plants' growth faster in the first stage of elongation (0% to 25%), whereas, oppositely, organic mulch made growth slower in the same stage. Eventually, this reduced duration of the 0% to 25% substage resulted in a higher root biomass.

In line with latest research findings (Marceddu et al., 2020; Rossini et al., 2016, 2021), it is therefore possible to state that, in the Mediterranean environment, the farming suitability of hops is highly variable among varieties. Further long-term research will focus on the relationship between root system development and plant productivity in hops, also pointing out the effects of cropping management on epigeal and hypogeal development, to ensure a higher sustainability in time of this crop.

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