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Analysis and agrometeorological modelling of grapevine responses to different trellising systems

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Summary

As the greater part of current viticulture is based on traditional trellising systems, usually in single hedgewall training, the aim of this research is to evaluate the possibility of introducing alternative trellising systems in order to improve canopy architecture and leaf distribution, and optimize light interception. In 2001 and 2002 field measurements (agrometeorological variables, vegetative growth, productivity and physiological behaviour) and modeling were performed on Sangiovese grapevines in a Tuscan vineyard with two trellis systems: a single hedgewall and a low double hedgewall (lyre trellis). The vines were spur pruned and cordon trained and the planting density was 6,667 vines/hectare. The two trellising systems were distributed in a randomized block design with 4 replications of 3 rows each. Data were collected from the central row. The simulation was obtained using a model, implemented with the Stella language, consisting of three sub-modules concerning photosynthesis, respiration and biomass accumulation. Light interception was greater for the lyre system than for the single cordon, while no differences were obtained in single leaf photosynthesis measurements between the trellis systems. Vegetative growth was higher for the lyre, indicating that lyre had a higher whole plant photosynthesis. The lyre system had greater yield due to a higher cluster number and a higher cluster weight compared to the single cordon training. No differences in must sugar content, titratable acidity or anthocyanins were observed. Models satisfactorily simulate the growth of grapevine under the single cordon system, while the growth of the lyre vine was extremely underestimated.

Key words: *Vitis vinifera*, single cordon, lyre trellising, light interception, dry matter accumulation, canopy architecture, spur pruning.

Introduction

Canopy architecture and leaf distribution in grapevines (*Vitis vinifera*) are mainly affected by the pruning and trellising system. Canopy management can play an important role in regulating the balance between vegetative growth and productive potentiality (CARBONNEAU 1990), but also

in the creation of optimum microclimate and light interception. Therefore, trellising system choice is very important, but also problematic, as numerous parameters must be taken into account, to meet grape grower goals (CARBONNEAU 1990, OLLAT and CARBONNEAU 1992, IACONO *et al.* 1995, MATTII and STORCHI 2000, 2001). These goals can be pursued with several technical choices, where canopy architecture and spatial shoot distribution play an important role as they can affect numerous ecophysiological and morphological parameters (INTRIERI 1987, CARBONNEAU 1996), such as sunlight interception, light penetration inside the canopy, sun-flecks, canopy and vineyard microclimate, flower induction, leaf area index, shoot, leaf and cluster growth, grape maturation, carbohydrate partitioning and so on (OLLAT and CARBONNEAU 1992; MABROUK *et al.* 1997).

The application of simulation modelling may offer significant benefits to a wide variety of activities, ranging from research to teaching and management of crop cultivation (MARCELIS *et al.* 1998; ORLANDINI 1998, ATKINS 1999). Grapevine growth and development have been considered in several modelling studies (BINDI *et al.* 1997; MORIONDO *et al.* 2000), based on different approaches, ranging from simple statistical relationships (REYNOLDS and ACOCK 1985), to the realisation of complex models, the application of which requires a large number of input variables (WHISLER *et al.* 1986). Few examples are available concerning the use of models for the analysis of grapevine responses to technical or environmental variables (PALCHETTI *et al.* 1995).

On the basis of these considerations, this research was performed with the aim of analysing and modelling grapevine responses to single cordon and lyre trellising systems. Field measurements were performed on Sangiovese variety and Stella simulation language was used, recently adapted to the simulation of grapevine biomass accumulation using agrometeorological and ecophysiological driving variables (LAKSO and JOHNSON 1990; LAKSO 1992; PONI *et al.* 2006). The results were discussed in order to evaluate the possibility of introducing alternative trellising systems to the single hedgewall for increasing canopy light interception.

Material and Methods

Experimental field: Research was carried out in 2001 and 2002 on a “Sangiovese” vineyard grafted onto a 420A (Berlandieri x Riparia) rootstock, located in

the southern part of the Brunello di Montalcino production area, in the South of Tuscany, Italy (43°03' lat. N and 11°29' long. E). The climate is typically Mediterranean, with hot dry summers and relatively mild winters; rainfall is around 450-500 mm per year, mainly distributed in autumn and spring. Soil is within the average of the area, with a high percentage of clay (42 %) and some rocks. The vineyard is located in a hilly area with a southern exposure; row orientation is NW-SE and planting distance is 3 x 0.5 m. Eight-year-old vines were trained upwards on single and double spur cordons (lyre). Single cordon represents the typical system of Tuscany, allowing to obtain a very good quality in areas characterised by low vigour, as is often possible to find in Tuscan viticultural environments. Lyre trellising was developed in France, with the aim of reconciling high production and good wine quality (OLLAT and CARBONNEAU 1992).

The lyre was established with two vertical hedgewalls at a distance of 80 cm (40 cm from the center of the row). The vine trunk was vertically trained up to 70 cm, then divided into two horizontal branches to reach lateral wires at the base of each hedgewall, where the two lyre spur-pruned cordon was established (Fig. 1). At pruning time, 5 buds per plant were left on the cordon, while 10 buds per plant (5 per cordon) were left on the lyre system. In both trellising systems shoots were upward positioned and trimming was not carried out. Treatments were distributed according to a randomized block design with 4 replications

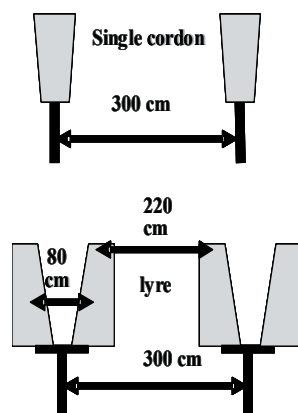


Fig. 1: Trellising systems outline.

consisting of 3 rows each; measurements were performed from the central row.

Field measurements

Agrometeorological variables: A complete agrometeorological station has been deployed over turf just outside the vineyard for the measurement of air temperature (°C) (Vaisala HMP45, Helsinki, FI), relative humidity (%) (Vaisala HMP45, Helsinki, FI), precipitation (mm) (RGB1 Institute of Hydrology, Wallingford, UK) and global radiation ($W m^{-2}$) (Skye E031, Llandrindod Wells, UK). All the sensors were connected to a data logger (Delta-T Devices DL2, Burwell, Cambridge, UK) and data were recorded every hour.

Biomass production and partitioning: shoot elongation was detected by measur-

ing 12 shoots per treatment (3 per replication) with a two-week interval starting from two weeks after budbreak to the end of growing season. At the same time, leaf number, as well as lateral numbers and leaf numbers from lateral shoots were counted. Destructive measurements were performed collecting 12 shoots/treatment at the day-of-the year 155 (June 4, flowering), 178 (June 27, after fruit set), 211 (July 30, veraison) and 265 (September 22, harvest). Shoots were separated into their different organs: principal leaves, principal shoot, lateral leaves, lateral shoots, and berries. Leaf area was measured using a Laser Area Meter (Cid Inc., USA); all the parts were weighed separately and then dried to a constant weight in the oven at 70 °C. These data were translated on a vine basis by multiplying single shoot values by the number of shoots/vine.

Light interception: Data were collected horizontally at 10 cm above ground from an area of 3 x 0.5 m using a ceptometer (Decagon, USA); measuring grid was 1 x 10 cm with 5 lines every 10 cm along the row length. Sensor distance in the ceptometer was 1 cm. Readings were collected from 12 vines per trellising system on sunny days from 1 month after budbreak until harvest (day of the year 137 - May 17, 155 - June 4, 164 - June 13, 172 - June 22, 210 - July 30, 217 - August 5, 220 - August 8, 259 - September 16), at different times during the day (8 and 10 a.m., noon, 2 and 4 p.m.) to obtain an average daily canopy light interception.

Leaf gas exchange: readings were performed using an infra red gas analyzer Ciras 1 (PP Systems, Herts, UK) at the same time as light interception measurements on 6 healthy, fully expanded and well exposed leaves/replication positioned in the middle part of the principal shoot. Net photosynthesis (A), transpiration (E) and stomatal conductance (Gs) were measured; water use efficiency (WUE) as A/E ratio was also calculated.

Plant production: 6 vines per replicate from each trellising system were harvested on 18 September 2001 and 16 September 2002; clusters per plant were counted and weighed separately. Moreover, two 300 berry samples per replicate were collected for both must and anthocyanins analyses; the must analyses were performed after squeezing the sample berries for the following ripeness parameters: sugar content, using a hand refractometer and reading the Brix degree; titratable acidity, by titration of 10 ml of must sample with NaOH 0.1 N to pH 7; pH. The anthocyanins analyses were performed according to the Glories method (1984); anthocyanins content and extractability were also detected.

All data were subjected to variance analysis, with mean separation via the LSD test ($p \leq 0.05$) (SPSS 8.0 software, 1997).

Grapevine growth model: The model was implemented using the simulation language STELLA 7.0.3, a compiler GPST (General Purpose Simulation Tools) allowing the development of simple or complex models in an easy manner by using a graphic interface. The first applications to model crop growth and development were proposed at the beginning of '90 for apples (LAKSO and JOHNSON 1990; LAKSO 1992). At the beginning of 2000

the simulation model was adapted to grapevines (LAKSO *et al.* 2000). In Italy a research project, supported by the Ministry of University, was performed with the aim to verify and validate grapevine model performances in different environmental and technical conditions (PONI *et al.* 2003, 2006).

The model simulates grapevine growth considering the biomass accumulation as the budget of photosynthesis and respiration processes. To reduce the complexity, the root system was not taken into account. The simulation starts at budbreak and ends before harvest, with a daily time step. In the photosynthesis sub-module, agrometeorological inputs are maximum and minimum temperatures, global solar radiation and day length. Crop inputs are maximum net photosynthesis, intercepted solar radiation, and photochemical efficiency of leaf. All these inputs were measured in field on each trellising system, however for the last one the same values were used for both systems. This original formulation has been made for continuous canopies; in grapevine, this pattern would introduce a considerable error for any hedgerow-trained vineyard. Therefore the model was adapted to the experiment conditions by introducing several coefficients concerning radiation extinction depending on canopy shape and the area covered by each plant, and function of layout of planting (PONI *et al.* 2006). On this basis the model calculates the effect of temperature on the rate of daily photosynthesis, the rate of daily photosynthesis, and from these, the daily photosynthesis itself (CHARLES-EDWARDS 1982).

In the respiration sub-module, agrometeorological inputs are maximum and minimum temperatures and day length. Grapevine inputs are leaf area, shoot area, fresh weight of cluster, number of clusters per vine. To simulate crop respiration, organ temperatures are first calculated according to LAKSO and JOHNSON (1990) and then the values obtained are used as exponential function input based on the relationship between respiration and temperature.

Finally, respiration and photosynthesis values are added to calculate daily carbon balance and then grapevine biomass accumulation, expressed in grams of dry matter per vine.

Results and Discussion

Biomass production and partitioning: Shoot elongation (Fig. 2) showed the same pattern in the two trellising systems and in both years single cordon showed a higher shoot growth. In 2001 the growth stopped in the second half of July in both treatments, and near the end of June in 2002 in both treatments. No differences were observed in the number of leaves per shoot due to the lower internode length in lyre (data not shown); consequently, a higher leaf number per plant was detected in lyre system due to the higher shoot number (10 buds per vine versus 5 buds per vine in the spur cordon). Laterals per shoot were higher in single cordon, but the number of laterals per plant was similar in both trellising systems (data not shown). Nevertheless, the single cordon laterals were

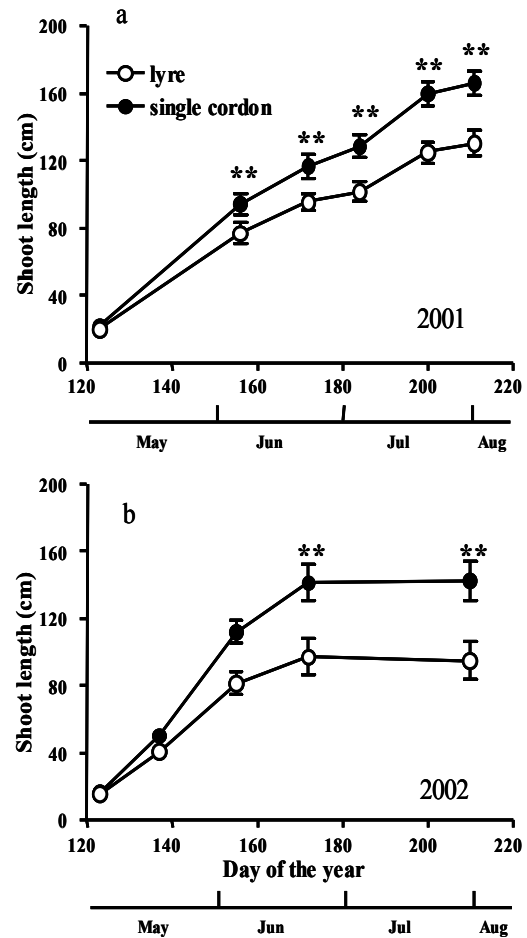


Fig. 2: Shoot elongation as affected by trellising system in 2001 (a) and 2002 (b) (** = statistical difference $P \leq 0.01$). Vertical bars represent SD.

much more vigorous, so that their average of single leaf area was higher in the single cordon with 142 cm^2 versus 74.3 cm^2 in the lyre system (average of both years). Total leaf area per vine was higher in lyre in 2001 versus single cordon, where, in 2002 no differences were observed. The leaf area composition was quite different in the two different kinds of canopies (Fig. 3): lyre total leaf area belongs mainly to the principal leaves, whereas total single cordon leaf area comes mainly from laterals. Cluster dry weight

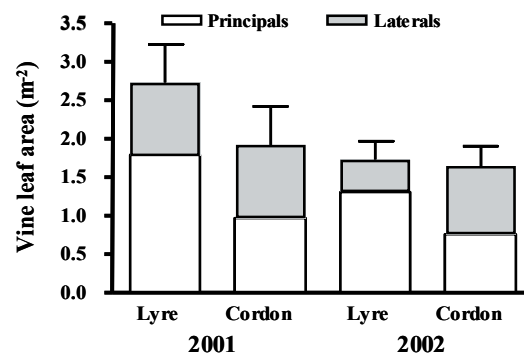


Fig. 3: Vine leaf area distribution at harvest time as affected by different trellising systems (vertical bars represent statistical difference $P \leq 0.05$ within each year for the total leaf area).

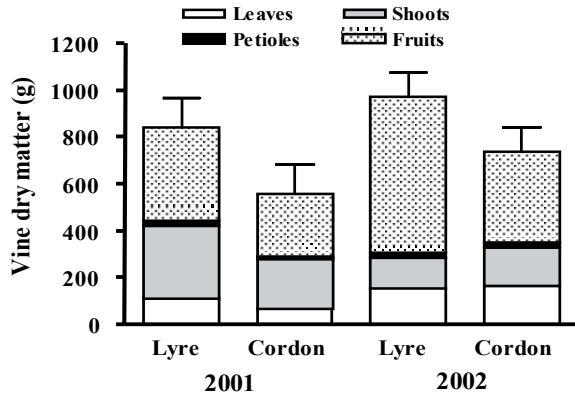


Fig. 4: Dry matter partitioning at harvest time in the different trellising systems (vertical bars represent statistical difference $P \leq 0.05$ within each year for the total dry matter).

was higher in lyre, and the percentage of clusters per total dry matter was similar in 2001 (47 %), while in 2002 it was 68 % in lyre and 52 % in cordon trellising (Fig. 4). The different biomass partitioning in the two years can be due to the higher and longer shoot growth in 2001 that led to a predominance of vegetative activity.

Light interception: Light interception values are quite low in 2002, with a maximum of 24.3 % in single cordon and 31.6 % in lyre system as a daily average (Fig. 5). On the other hand, in 2001 values were higher, with a maximum of 52 % in lyre and 32 % in single cordon. Values are quite low due to the planting distances: high inter-row spacing compared to small distances between plants that lead to quite small canopies. The high percentage of laterals in the single cordon and the presence of gaps in the lyre canopy affected light interception: the differences between the two trellising systems were quite low especially in 2002. The ideal canopy should be continuous in the row, like single cordon, but it should have few leaf layers as in lyre, because the interior layers of leaves have a low photosynthetic efficiency (PONI *et al.* 2000).

Gas exchange: First of all the two years showed a different pattern of photosynthesis due to the different rainfall trend (Tab. 1); after an initial increase up to bloom (usually at the beginning of June in Tuscany), net assimilation decreased in both trellising systems in 2001 (Fig. 6), possibly due to the low water availability (Tab. 1).

In 2002, on the other hand, the assimilation of the sampled leaves of lyre showed a decrease after bloom followed by an increase in the last part of the season, while the sampled leaves of the single cordon remained quite stable.

As reported in previous research (WILLIAMS 2002) water consumption is directly correlated to light interception; so vines with higher light interception are more subjected to water stress. The lower values in lyre trellising, although not statistically different, can be presumably due to a moderate water stress from the end of June to the beginning of August, when the heavy rainfall may have increased leaf photosynthesis (Tab. 1).

The same pattern has been observed in stomatal conductance (data not shown): consequently, single leaf water use efficiency was not affected by the trellising system.

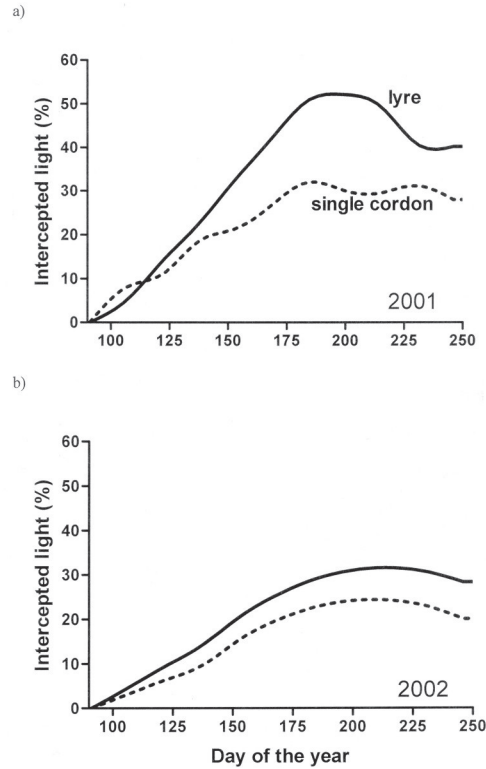


Fig. 5: Interpolated trend of daily average light interception in 2001 (a) and 2002 (b).

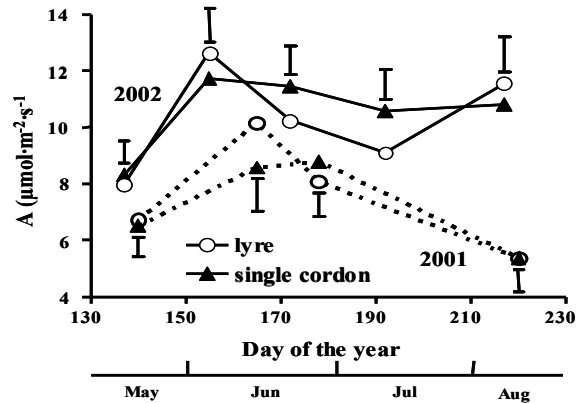


Fig. 6: Net photosynthesis (A) as affected by different trellising systems (vertical bars represent statistical difference $P \leq 0.05$ within each year).

Table 1

Monthly rainfall (mm) in Montalcino in 2001 and 2002 during the grapevine growing season

Year	April	May	June	July	August
2001	81	46	20	17	5
2002	43	80	38	41	183

Plant production: In general the two years showed the same pattern: productive measurements pointed out that lyre produced a higher cluster number per plant, leading to a higher yield per plant, thanks to their average weight as well (Tab. 2). Although these results, single cor-

Table 2

Productive characteristics (quantity and quality) of grapevines trained to lyre and single cordon
(* = statistical difference $P \leq 0.05$)

	2001			2002		
	lyre	cordon		lyre	cordon	
Yield/vine (kg)	2.23	1.13	*	2.7	1.5	*
Clusters/vine	6.9	5.0	ns	11.3	7.0	*
Cluster weight (g)	323	226	*	243	217	*
Berry weight (g)	2.15	2.09	ns	2.02	2.08	ns
Must Brix ^o	21.9	21.5	ns	22.3	21.7	ns
Titrateable must acidity (g·l ⁻¹)	7.85	8.06	ns	7.03	8.11	*
Anthocyanin content (mg·l ⁻¹)	1158	1074	ns	1384	1328	ns
Anthocyanin extractability (%)	49	52	ns	58	54	ns

don showed the higher fertility (1.2 cluster number per node versus 0.9 as the average of 2001 and 2002). Berry weight, on the other hand, failed to show any statistical difference, leading to the hypothesis that cluster weight is mainly affected by a higher fruit set percentage and, consequently, a higher berry number per cluster. Better lighting conditions inside the canopy in the lyre system might affect light interception at cluster level with a consequently higher fruit set (FERREE *et al.* 2001). Another hypothesis could be considered by taking into account the higher vigour showed by single cordon that leads to a higher shoot growth and, therefore, more competition between vegetative and productive activity, and a lower fruit set. In a vigorous shoot, in fact, the apex is a strong sink for metabolites, and clusters can be penalized by this activity, failing to finish their development and showing a lower fruit set percentage (PONI *et al.* 1993; MATTII and FERRINI 2004). This topic is worth analysing in depth with further research, also because berry number per cluster in lyre system could be increased by a higher number of flowers (FERREE *et al.* 2001).

Must qualitative characteristics at harvest (Tab. 2) failed to show differences between the two trellising systems regarding sugar content, berry anthocyanin content or anthocyanin extraibility; the only difference was detected in must titrateable acidity in 2002, higher in single cordon than in lyre. A higher acidity value at harvest is usually linked to a maturation delay. In conclusion, by using the lyre system no difference in production qualitative characteristics was observed; probably the better shoot distribution allowed for better light utilization inside the canopy, together with better air circulation, allowing for good cluster maturation in spite of the higher plant yield (MATTII and STORCHI 2001).

Grapevine growth model: Due to the higher biomass, respiration simulations were constantly higher in lyre plants than in single hedgewall ones. However, the trend was similar for both trellising systems, with total respiration constantly increasing from budbreak until June mainly due to the contribution of shoots. After bloom the values were quite constant with a slight decreasing until the latter part of the season (data not shown).

Calculated daily photosynthesis per vine showed a fast increase from budbreak until the end of June in 2001 in

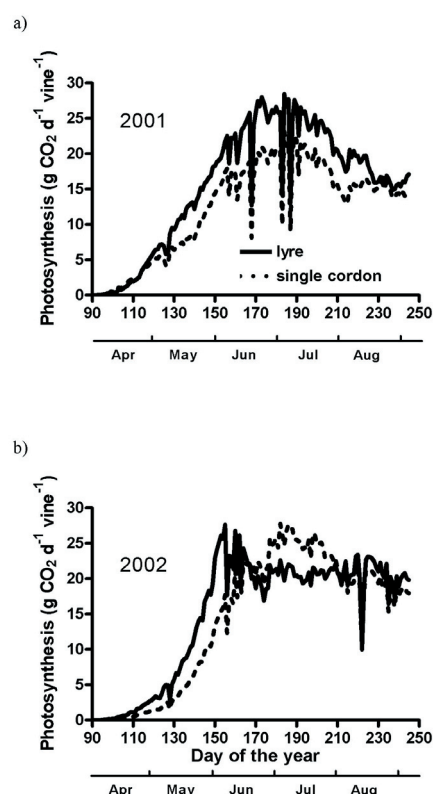


Fig. 7: Seasonal trend of simulated daily photosynthesis for lyre and single cordon in 2001 (a) and 2002 (b).

both trellising systems and in 2002 only for single cordon. Lyre vines had higher values of whole vine photosynthesis throughout all the season in 2001 and only in the first part of the season during 2002 (Fig. 7). Subsequently the photosynthesis was quite constant in lyre plants with daily variations due to the pattern of solar radiation, while single cordon showed a further increase due to the higher single leaf assimilation (Fig. 6). In 2001, on the other hand, lyre vines assimilation rate was always higher than single cordon, and both decreased from the beginning of July due mainly to the decrease in single leaf photosynthesis as shown before (Fig. 6).

The combined effect of respiration and photosynthesis determined a different trend in the carbon balance (Fig. 8). In 2001 the calculated carbon gain in lyre was lower than

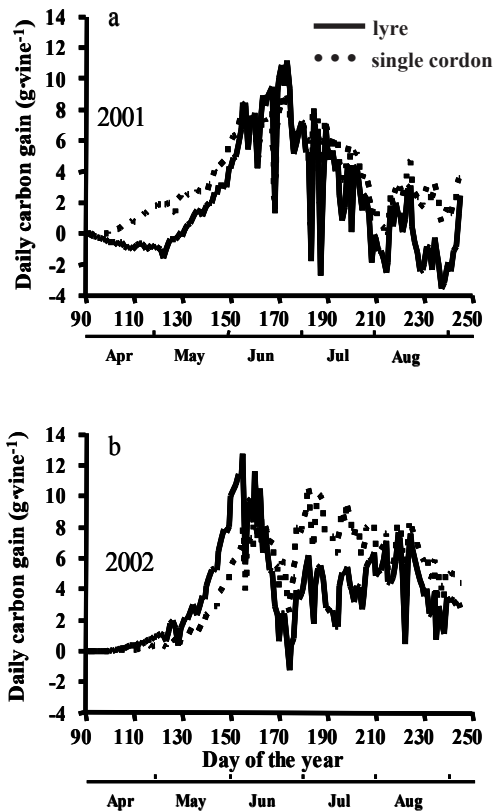


Fig. 8: Simulated daily carbon balance for compared trellising systems in 2001 (a) and 2002 (b).

in cordon during almost all the season, especially in the first 50 d and in the last part of the season. Only in the last two weeks of June lyre showed higher carbon gain than single cordon. This behaviour in the model was probably due to the higher leaf area, that means high whole vine respiration not balanced by high vine photosynthesis (Fig. 6).

In 2002, even though in the first part of the season lyre vines showed a very fast increase of daily carbon gain, after bloom the latter was very low and in some cases negative. On the contrary, single cordon carbon balance was higher and quite constant during the remaining part of the season.

Finally, by comparing observed and simulated values of total biomass, model performances in both years were very satisfactory for single cordon plants, while for lyre plants the model underestimated biomass accumulation, with extremely high differences at the end of growing season (Fig. 9). This was probably due to a better efficiency of the lyre system, which was able to assimilate a higher amount of CO₂ with respect to the quantities simulated according to light interception and ecophysiological variables used as input by the model. The better spatial distribution of leaf apparatus appeared particularly significant, allowing for a more efficient interception of solar radiation in lyre plants (Fig. 10). By classifying the radiation values measured by each ceptometer sensor below single vines in terms of frequencies, the single cordon had higher interception frequency in extreme classes (200 and 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), while at the intermediate classes (more active for photosynthesis) lyre showed higher interception.

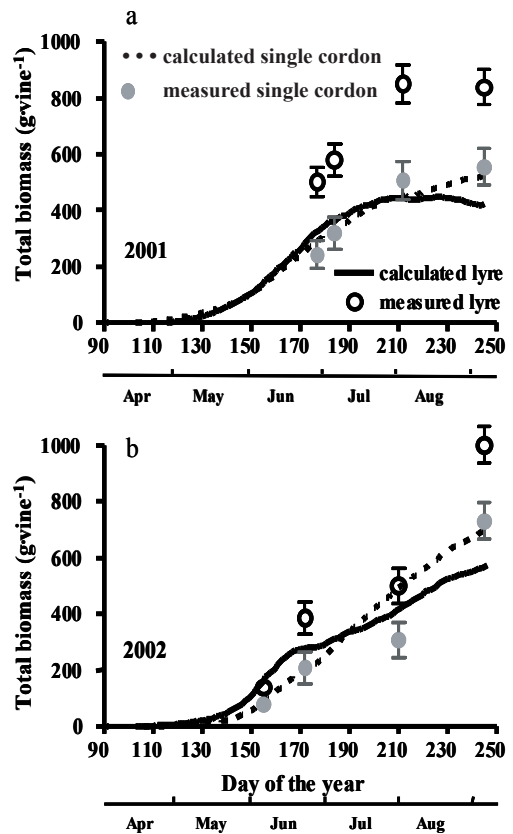


Fig. 9: Measured and simulated total biomass for lyre and single cordon in 2001 (a) and 2002 (b) (vertical bars represent SD).

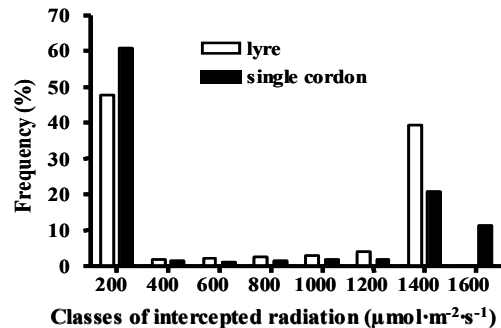


Fig. 10: Average frequency of intercepted solar radiation measured by each ceptometer sensor underneath representative vine per each trellising system on July monitoring day.

As lyre showed the highest light interception, whole plant photosynthesis should be higher compared to single cordon; in fact, single leaf photosynthesis failed to show any statistical difference between the two trellising systems, as reported in other research (OLLAT and CARBONNEAU 1992). Whole plant photosynthesis could be measured directly with methods already used in grapevines (PONI *et al.* 1997, MATTI and ORLANDINI 2004) or in other species (LAKSO *et al.* 1996). Model can be improved using leaf area instead of light interception in the carbon assimilation. In this case, leaf photosynthesis must be weighted considering the different classes of light interception inside the canopy. In other words, as appears from data, lyre has a similar light interception, but a less dense canopy, that means a higher percentage of leaves that intercept efficient

amount of light. The simple utilization of maximum net photosynthesis and light interception cannot work in this kind of trellis, as it has been set for a single canopy (PONI *et al.* 2006).

Conclusions

Lyre showed a higher productive efficiency compared to single cordon: considering vegeto-productive balance as the total leaf area per yield ratio on a plant basis, values of $0.9 \text{ m}^2\cdot\text{kg}^{-1}$ for lyre and $1.5 \text{ m}^2\cdot\text{kg}^{-1}$ for single cordon were achieved as the average of the two years. Despite this big difference in the vegetative/productive activity ratio, the plant production qualitative characteristics are similar. The lyre trellising system produced nearly double the biomass than the value calculated by the model, emphasising how the lyre canopy has a higher efficiency and is able to support a higher yield with the same leaf area.

Nevertheless, it is important to consider that in spite of a higher canopy efficiency, this kind of trellising system is quite difficult to mechanize (especially for harvesting and winter pruning), which is the advantage of the single cordon. On the other hand, the single cordon showed a higher source activity than sink demand and this surplus derived from vegetative activity, mainly laterals, creating quite a different canopy from that of the lyre system. In some cases, it could be useful to decrease the row spacing to reduce vine vigour and increase production per surface unit, as indicated in previous research (MATTII and STORCHI 2001).

Further improvements in model simulation will be addressed to provide a better evaluation of leaf area growth and grapevine development, in order to take into consideration source and sink balance and partitioning coefficients. Moreover, in order to increase the quality of simulations with the lyre trellis too, the photosynthetic effect of direct and diffuse solar radiation should be taken into account, as well as the different carbon balance of leaves produced by primary and lateral shoots. To take into account the light distribution inside the canopy and the percentage of light-exposed leaves could be another improvement of the model finalised to better simulate the values of intercepted radiation. Canopy measurements of gas exchanges will also be performed to evaluate total plant assimilation, for improving both model validation and the analysis of grapevine responses to the trellising system.

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