Vitis 36 (2), 67–71 (1997)

A simple model for simulation of growth and development in grapevine (*Vitis vinifera* L.). I. Model description

by

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S u m m a r y : A simple simulation model for growth of grapevine (*Vitis vinifera* L. cv. Sangiovese) is presented which mainly bases on analytical results from field experiments with plants free of visible stress and diseases. In the model leaf area development is defined as a function of temperature, biomass accumulation as a function of intercepted radiation and fruit growth is calculated from a linear increase of the fruit biomass index with time. The assumptions are discussed and comparisons between simulated and measured results are shown.

K e y   w o r d s : simulation model, dry matter partitioning, growth.

Introduction

A number of approaches have been used to analyse the effects of environmental variables on crop growth. In statistical approaches regressions were obtained correlating environmental variables and yield (review: Reynolds and Acock 1985). The main problems with statistical approaches are that yield estimation is more complex than growth simulation and that there is little confidence in extrapolating the results beyond the original limits of the data sets. Since the 1970s, mechanistic models have been developed (review: Whisler *et al.* 1986). Usually, difficulties in using these complex models arise from the numerous assumptions. An intermediate approach between the statistical and the complex methods is to use simplified mechanistic models which define crop behaviour by only a few relationships. Recently, this approach has been used to study the influence of environmental parameters on growth and yield of several crops, i.e. soybean (Spaeth *et al.* 1987), maize (Muchow *et al.* 1990) and wheat (Amir and Sinclair 1991).

In this paper, a crop growth model for grapevine is formulated following this latter approach; it has been parameterised by means of experimental observations on the cultivar Sangiovese. In a second paper the model is validated by means of independent observations and is applied for the simulation of growth of the cultivar Cabernet-Sauvignon.

Materials and methods

F i e l d   a n d   w e a t h e r   d a t a : 20-year-old grapevines (Sangiovese) grafted on 420 A at the Mondeggi-Lappeggi Farm in the Chianti Region in Italy (Lat. 43.75 °N, Long. 11.35 °E) were used to develop and parameterise the model. Vines were grown 3 m x 1 m, cordon trained (vertical trellises) and spur pruned with on the average 11 buds per vine. The soil was a clay loam with a volumetric water content of about 0.40 $cm^3 \cdot cm^{-3}$. Cultural practices included the usual abundant fertilisation and a complete set of treatments against major fungus diseases.

In 1992, from May to September, entire shoots were sampled (including lateral shoots) at 3-week intervals. Per sampling date non-adjacent and representative plants of the vineyard were chosen and one shoot per plant was harvested; samples were taken from individual vines only once. The shoots were transferred in plastic bags to the laboratory, where the leaf area was determined with a LI-COR area meter (Model 3050-A). The number of leaves and clusters of all shoots were determined. The dry weight of leaves, stems, berries and grape stalks were measured after drying at 70 °C. The fruit biomass index (FBI) was calculated from the ratio of berry dry weight related to the dry weight of the annually grown biomass, i.e. leaves +stems+grape stalks+berries.

Solar radiation and air temperature were measured with a SKY pyranometer (Model E031) and a thermistor, respectively. The sensors were located close to the vineyard (about 10 m) and the output was monitored with a Delta-T data logger.

M o d e l   d e s c r i p t i o n : Relatively few relationships are used in this model to describe the development, growth and yield of grapevine (Fig. 1, Tab. 1). The major processes simulated are ontogeny, leaf development, biomass accumulation and fruit growth.

O n t o g e n y : Grapevine ontogeny can be divided in two periods: a vegetative period between bud break and bloom and a fruit growth period between bloom and maturity. On the analogy of McIntyre *et al.* (1982), phenological observations collected from 1965 to 1970 on 123 cultivars

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Table 1

Definition of symbols

Variables	Description	Values, Units
State		
ADUR	accumulated TU during the lag phase	°C d
BIO	total biomass dry matter	g m^{-2}
FBI	fruit biomass index	-
FRU	fruit biomass dry matter	g m^{-2}
LAI	leaf area index	m^2 m^{-2} ground
SDUR	accumulated TU during the fruit growth phase	°C d
SLN	shoot leaf number	number
SLA	shoot leaf area	m^2
Other variables		
PHO	daily photosynthesis	g m^{-2} d^{-1}
RLF	leaf number rate	leaf d^{-1}
TU	thermal unit (Tmd - Tb, Tb = 10 °C)	°C d
Plant parameters		
a, b, c	coefficients in SLN equation	-0.28, 0.04, -0.015
d, f	coefficients in SLA equation	5.39, 2.13
COV	proportion of the area shaded by the plant	0.75
RUE	radiation use efficiency (total radiation)	1.001 g MJ^{-1}
K	extinction coefficient of canopy	0.5
LAG	duration of lag phase in TU	40 °C d
MAT	duration of fruit growth phase in TU	1440 °C d
NS	number of shoots per plant	11
PLA	planting density	3 m^2 per plant
SLOPE	rate of change in FBI	0.00443 d^{-1}
Environmental		
Rad	daily global solar radiation	MJ m^{-2} d^{-1}
Tmd	daily mean temperature	°C
Tmn	daily minimum temperature	°C
Tmx	daily maximum temperature	°C

of *Vitis vinifera* L. grown in an experimental vineyard at the station of Conegliano, Italy (CALÒ and COSTACURTA 1973) were used to evaluate the reliability of climatic and biological indicators for the prediction of developmental stages. Data were classified on the basis of earliness of varieties in two data sets (early and late cultivars) and meteorological data were obtained from a station which was less than 1 km away from the vineyard.

For each data set the mean (AVG), standard deviation (SD, expressed in equivalent days) and the coefficient of variation (CV) of various indicators for three developmental stages (i.e. physiological dormancy-bud break[1]), bud break-bloom, and bloom-maturity) were calculated. The CV, which is the percentage ratio of the standard deviation and the mean, and which has a value of zero if there is no annual variation, is a useful measure of the indicator's consistency. In particular, the reliability of the first 5 indicators (number of days, degree days, cumulative maximum

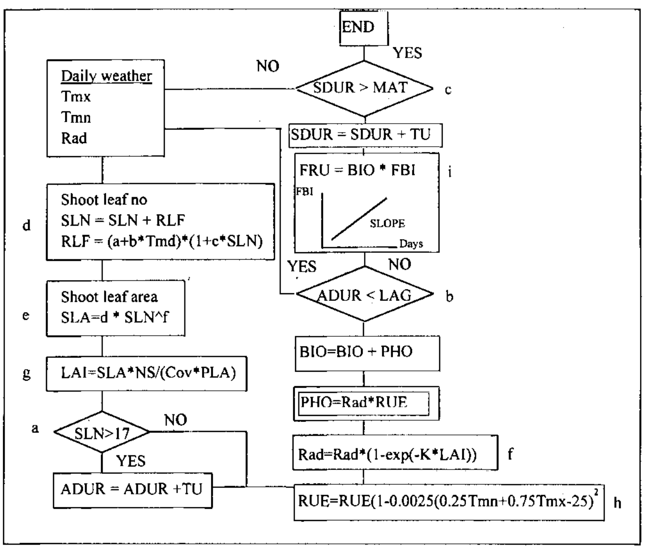

Fig. 1: Flow diagram of the model for simulating growth and development of grapevine. List of symbols see Tab. 1. For details on letters see text (Materials and methods).

[1]) Bud break = stage C according to BAGGIOLINI (see CALÒ 1970).

Table 2

Indicators of developmental stages for early and late vine cultivars. AVG: average, SD: standard deviation (expressed in equivalent days) and CV: coefficient of variation

Indicator	January 1 to bud break			Bud break to bloom			Bloom to maturity		
	AVG	SD	CV	AVG	SD	CV	AVG	SD	CV
Early cultivar									
Number of days	103.5	6.7	6.4	54.7	7.6	13.9	101.7	7.8	7.6
Degree days[1])	27.4	40.9	39.5	314.5	2.5	4.5	1135.0	5.2	4.9
Cum. max. temperature[2])	1003.3	10.7	10.3	1169.4	5.1	9.3	2718.4	8.0	7.9
Cum. radiation[3])	9418.2	8.2	7.9	10682.7	5.5	10.1	20804.7	8.8	8.7
Cum. temperature diff.[4])	894.7	8.0	7.7	630.3	5.9	10.8	1133.6	10.3	9.2
Leaf number	-	-	-	16.8	2.8	5.1	-	-	-
Pouget model	1495.5	13.6	13.1	-	-	-	-	-	-
Late cultivar									
Number of days	107.5	7.8	7.2	53.2	6.6	12.4	119.5	6.4	5.3
Degree days[1])	34.1	40.8	37.9	330.4	1.9	3.5	1242.0	4.7	4.2
Cum. max. temperature[2])	1067.0	11.1	10.3	1167.8	4.3	8.2	3088.2	5.1	4.2
Cum. radiation[3])	9981.8	10.0	9.3	10648.5	5.2	9.9	22950.5	7.4	6.2
Cum. temperature diff.[4])	933.1	7.7	7.2	620.6	5.7	10.8	1307.8	8.8	8.0
Leaf number	-	-	-	17.2	2.0	3.8	-	-	-
Pouget model	1163.0	14.3	13.3	-	-	-	-	-	-

[1]) Degree days $\sum_{i=1}^{n}\left(Tmd_i - Tb\right)$

[2]) Cum. max. temperature = $\sum_{i=1}^{n} Tmx_i$

[3]) Cum. radiation = $\sum_{i=1}^{n} Rad_i$

[4]) Cum. temperature diff. = $\sum_{i=1}^{n}\left(Tmx_i - Tmn_i\right)$

temperature, radiation and temperature difference) has been evaluated for all three phases (Tab. 2), whereas the reliability of leaf number[2]) has been evaluated for the interval from bud break to bloom and the Pouget formulae[3]) (POUGET 1988; RIOU and POUGET 1992) have been evaluated for the interval from January 1 to bud break, only.

In model parameterisation the onset of the growing season was equated with the observed date. The duration of the period between bud break and bloom was calculated by equating the number of leaves (SNL) on a primary shoot with 17 at bloom as a function of the rate of appearance of leaves (Fig. 1 a). The duration of the period between bloom and maturity was calculated as a function of cumulative degree days during this period. The period was divided into two sub-phases which are the period between bloom and fruit set and the period of fruit growth. Using data collected in 1992, intervals between bloom and the onset of fruit growth (LAG) and between fruit set and maturity (MAT) were set to 40 and 1440 degree days, respectively (Fig. 1 b-c).

[2]) The formation of new leaves on shoots is closely correlated with the development of flowers such that anthesis (full bloom) occurs when the shoot has 17-18 visible leaves (PRATT and COOMBE 1978).

[3]) The method predicts the date of bud break on the basis of the sum of the daily minimum and maximum temperatures starting from a fixed date, e.g. January 1.

L e a f a r e a : Leaf area was estimated from the number of actively growing shoots and the rate of leaf appearance and expansion. The rate of leaf appearance was calculated using a model (MIGLIETTA *et al.* 1992) which calculates the daily rate of leaf formation and appearance (RLF) after bud break on the basis of the mean daily temperature, assuming that the rate of leaf appearance declines during ontogeny (Fig. 1 d). Total leaf area per shoot (SLA) is then estimated as a function of total number of appeared leaves (SNL) using an exponential relationship (Fig. 2)

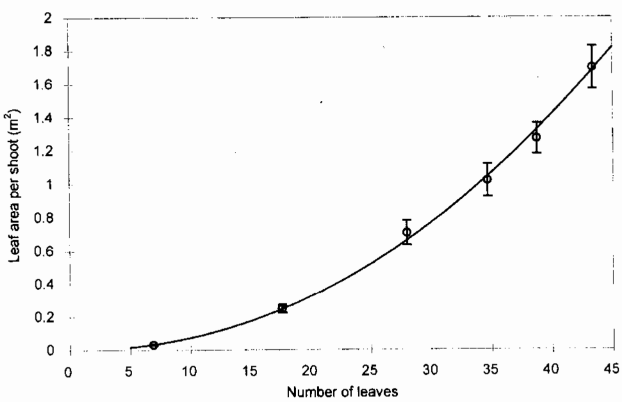

Fig. 2: Exponential regression describing the relationship between leaf number and leaf area per shoot for cv. Sangiovese. Vertical bars: standard error of the mean (n=10).

similar to those found for other crops, e.g. wheat, barley, etc. (BAKER 1985; AMIR and SINCLAIR 1991). Parameterisation of this equation used data collected during the 1992 growing season (Fig. 1 e).

Biomass accumulation: Leaf area, as calculated by the relationship described in the previous section, is used to calculate the amount of solar radiation intercepted by the leaf canopy (Fig. 1 f). The exponential equation for radiation interception as a function of leaf area index (LAI) has been established for many crops including grapevine (WERMELINGER and BAUMGARTNER 1991). LAI was calculated taking into account the proportion of area shaded by the plant (COV), and the plant density (PLA) (Fig. 1g). Crop biomass accumulation is then calculated from radiation interception using estimates of crop radiation use efficiency (RUE, biomass accumulated per unit global solar radiation intercepted). The assumption that the rate of crop biomass accumulation can be approximated by RUE is supported by many studies in which a linear correlation was found between canopy CO_2 uptake rates and the fraction of incident radiation intercepted if water is not limiting (SPAETH *et al.* 1987; MUCHOW *et al.* 1990; AMIR and SINCLAIR 1991). In our simulation, the value of RUE was calculated from the samples taken during the period between June and September 1992 (Fig. 3). In the model, RUE was set equal to 1.001 g MJ^{-1} throughout the whole growth period. Moreover, following the approach used in other simulation models (RITCHIE and OTTER 1984; VAN KEULEN and SELIGMAN 1987) the effect of low and high temperature on carbon uptake is introduced in the form of a second order function decreasing RUE for suboptimal temperature (Fig. 1 h).

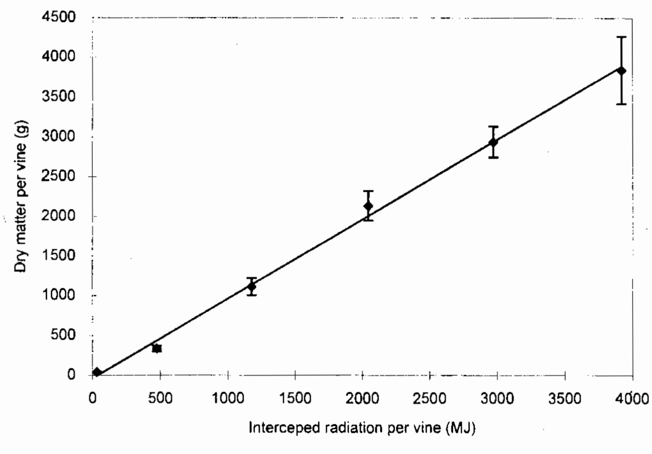

Fig. 3: Linear regression describing the relationship between accumulated dry matter and accumulated intercepted radiation per vine, cv. Sangiovese. Bars: see Fig. 2.

Fruit growth: Daily fruit growth rate was calculated on the basis of the empirical observation that fruit biomass index (FBI) increases linearly during fruit growth. A linear relationship between the ratio of grain to total above ground biomass (harvest index) and time was already observed for several species (SPAETH *et al.* 1987; MUCHOW *et al.* 1990; AMIR and SINCLAIR 1991). Data collected in 1992 confirmed the relationship even when fruit, rather than grain biomass, was considered (Fig. 4). The rate of increase in FBI (SLOPE) was set 0.00443 d^{-1} in the model. Daily fruit growth was calculated from the increase in harvest index (Fig. 1 i).

The description of this model confirms the possibility of applying the statistical/mechanistic approach not only for studying the influence of environmental parameters on growth and yield of annual crops, but also for perennial crops.

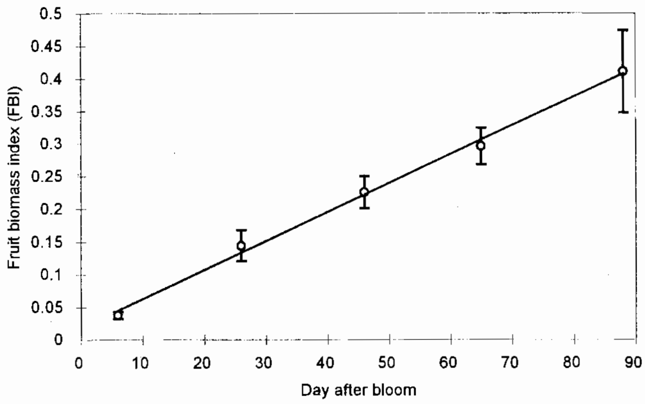

Fig. 4: Fruit biomass index (FBI) of grapevine, cv. Sangiovese, observed at 3-week intervals during 1992. Bars: see Fig. 2.

Results and Discussion

For the January 1 to bud break interval, none of the indicators provided a better estimate of the period than the number of days (CV 6.4-7.2%); for the bud break to bloom interval, degree-days (CV 3.5-4.5%) and leaf number (CV 3.8-5.1%) were the best indicators; and for the bloom to maturity interval, degree-days (CV 4.2-4.9%) was the most reliable indicator. For this developmental stage, however, all indicators show low reliability (high value of CV) due to the influence of viticultural practices and other factors (e.g. water balance) (Tab. 2).

Fig. 5 a-i show the daily extreme temperatures and solar radiation used to drive the model, and the data used to estimate the model parameters related to leaf number and leaf area, fruit, vegetative and total biomass dry matter. The computer simulations of the data are the solid lines and observation data are presented as vertical bars.

Although the observed growth of crops was simulated satisfactory, a tendency existed to overestimate vegetative dry matter during the late fruit-growth period (Fig. 5 f). This may be due to either an overestimation of radiation interception or of radiation use efficiency. Since leaf areas were in good agreement with measured data (Fig. 5 d), it is likely that radiation interception was also simulated realistically. Because radiation extinction coefficients and radiation use efficiencies are negatively correlated (STUTZEL and AUFHAMMER 1991), an overestimation of radiation use efficiency may possibly have been due to an increase of the radiation extinction coefficient in the senescing crops not accounted for in the model. Simulated number of leaves and fruit and total dry matter are in reasonable agreement with measured values (Fig. 5 a, c and e).

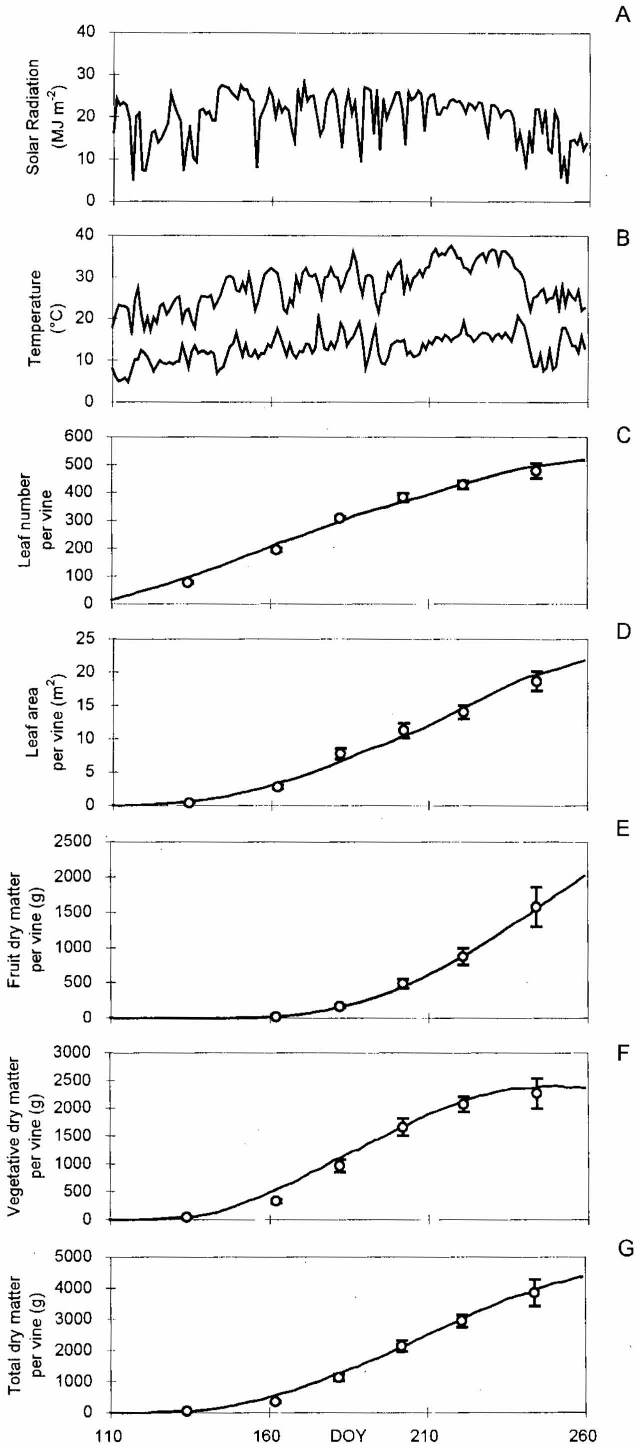

Fig. 5: Pattern of solar radiation (A), and minimum and maximum air temperatures (B) in 1992. Number and area of leaves, and dry matter of fruit, vegetative and total biomass components are plotted in C-G. The lines in C-G are simulated growth from model. DOY = day of year. Bars: see Fig. 2.

Conclusions

The model describes reasonably well the observed pattern of vine crop growth thus providing a good tool to simulate the development and growth of grapevine under field conditions. However, it must be stressed that with such a model, growth and yield of stress-free crops may be simulated only, and that the model was parameterised on the basis of a single observation data set. Therefore no evaluations for other years, varieties or locations are possible. For this reason grapevine growth was monitored over a two-year period. Results of these model validation tests together with considerations on possible application of the model will be presented and discussed in a following paper.

Acknowledgements

The authors thank the Provincia di Firenze, Assessorato all'Agricoltura and Dr. A. Paoletti, director of Santa Cristina farm, Chianti for the logistic and technical support; Prof. J.R. Porter for useful suggestions. This research has been supported by the Commission of EU (Project CLAIRE n. EV5VCT930294, Environment Programme).

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Received November 5, 1996