agronomy

Supplementary Materials

Supplementary Sections

S1. Equations to Extrapolate Hourly Temperatures

In the case in which hourly temperatures $T_r(h,n)$ were not available, and only minimum (T_{min}) and maximum (T_{max}) temperature were measured, the former was evaluated in the following way. First, $T(h,n)$, with h being the hour, was calculated from T_{min} and T_{max} as

$$T(h,n) = \begin{cases} T_{min}(n) + h * \dfrac{\left(T_{max}(n) - T_{min}(n)\right)}{12} & if \quad h \leq 12 \\ T_{max}(n) - (h-12) * \dfrac{\left(T_{max}(n) - T_{min}(n+1)\right)}{12} & if \quad h > 12 \end{cases} \tag{S1}$$

and subsequently hourly temperatures $T_r(h,n)$ were assumed equal to $T(h,n)$ with two limiting cardinal temperatures, T_{0Bc} = 5 °C and T_{MBc} = 25 °C:

$$T_r(h,n) = \begin{cases} 0 & if\ T(h,n) < T_{0\mathrm{Bc}} \\ T(h,n) - T_{0\mathrm{Bc}} & if\ T_{0\mathrm{Bc}} \leq T(h,n) \leq T_{MBc} \\ T_{MBc} - T_{0\mathrm{Bc}} & if\ T(h,n) > T_{MBc} \end{cases} \tag{S2}$$

S2. Parameterization of LAI

The *LAI* (m^2 m^{-2}), calculated in Equation (7) [45,46], was parameterized using

- a daily rate of expansion of leaf area (Δ_I) (m^2 $plant^{-1}$ $°C^{-1}$),

$$\Delta_I = \frac{LAI_{MAX}}{\left(1 + \mathrm{e}^{[PLAI_{MAX} * (VEL_{MAX} - U_{LAI})]}\right)} \tag{S3}$$

- the vineyard plant density *DENS* (plants m^{-2}), assumed equal to 0.40 plants m^{-2};
- a parameter set, described in detail in Reference [46], whose values are LAI_{MAX} = 0.015 m^2 $vine^{-1}$ $°C^{-1}$, $PLAI_{MAX}$ = 5.0, and VEL_{MAX} = 2.2;
- the development unit U_{LAI}, assumed varying between 1 and 3 [46];
- a function F_T of daily mean (T_{av}) and minimum (T_n) air temperatures (in °C), given by

$$F_T = T_{av} - T_n; \tag{S4}$$

- the water status index I_W, defined by the following equations [45,46],

$$if \begin{cases} WC \geq WC_{cr} \rightarrow I_W = 1.0 \\ WC < WC_{cr} \rightarrow I_W = 4.5\, WC \end{cases} \tag{S5}$$

S3. Parameterization of Berry Sugar Content

The function σ_{Brix} is a normalized number, lower than 1, given by

$$\sigma_{Brix} = E_{mg}\left\{1 - \mathrm{e}^{-[E_c(GDD_N - 0.095)]}\right\} + \frac{A}{1 + \mathrm{e}^{-[L_e(GDD_N - L_{mg})]}} - \frac{A}{1 + \mathrm{e}^{-[L_c(0.906 - L_{mg})]}} \tag{S6}$$

where A is given by

$$A = \frac{1 - E_{mg}\left[1 - \mathrm{e}^{-(E_c - 0.904)}\right]}{\dfrac{1}{1 + \mathrm{e}^{-[L_c(1 - L_{mg})]}} - \dfrac{1}{1 + \mathrm{e}^{-[L_c(0.096 - L_{mg})]}}} \tag{S7}$$

and the parameters E_C and E_{mg} represent the curvature and the point of maximum growth of the exponential function, L_C and L_{mg} are the curvature and the point of maximum growth of the logistic function, and GDD_N refers to the normalized growing degree days (the ratio between the actual value of *GDD* and the total value of *GDD* from flowering to harvest stages GDD_{tot}).

S4. Parameterization of Yield

The daily production of dry matter (*DM*, g m^{-2} day^{-1}) was calculated (Equation (S8)) as the product of the potential net assimilation (*PNA*) and the daily thermal (T_L) and water (W_L) limiting factors, the last two being both dimensionless and varying from 0 to 1:

$$DM(n) = PNA(n) \times T_L(n) \times W_L(n) \tag{S8}$$

The dry matter accumulation into vine clusters ($DM_{cluster}$, g m^{-2} day^{-1}) [22] was performed as

$$DM_{cluster}(n) = DM(n) \times C_{sink} \tag{S9}$$

where the multiplicative factor C_{sink} (that varies from 0 to 1) is evaluated using the ratio R_{berry} between the number of berries and the maximum potential value, and the number of clusters (N_c) as

$$if \begin{cases} N_c \leq 3 & \rightarrow \quad C_{sink} = 0.1 \\ N_c \geq 20 & \rightarrow \quad C_{sink} = 1 \\ 3 < N_c < 20 & \rightarrow C_{sink} = R_{berry}\left(a_4 N_c^4 + a_3 N_c^3 + a_2 N_c^2 + a_1 N_c + a_0\right) \end{cases} \tag{S10}$$

where $a_4 = -2 \times 10^{-8}$, $a_3 = 5.2 \times 10^{-5}$, $a_2 = -0.1 \times 10^{-3}$, $a_1 = 9.9 \times 10^{-2}$, and $a_0 = -1.6 \times 10^{-2}$ are empirical coefficients (discussed in Reference [22] but calibrated for cv. Nebbiolo by the authors).

In Equation (S8), the temperature limiting factor T_L is defined by [22,61]

$$T_L = \frac{\sum_h T_{LH}}{24} \tag{S11}$$

where T_{LH} represents the hourly values of the temperature limiting factor and, if not available, can be evaluated from the hourly temperatures $T(h,n)$ as [22,61]

$$T_{LH} = \frac{2[T(h,n) - 7]^a\{(25.5 - 7)^a - [T(h,n) - 7]^{2a}\}}{(25.5 - 7)^{2a}} \tag{S12}$$

and $a = 1.574$ is a coefficient.

The water limiting factor W_L in Equation (S8) is calculated adapting equations discussed in Reference [22] as

$$if \begin{cases} WC \leq WC_{cr} & \rightarrow \quad W_L = \dfrac{WC - W_P}{WC_{cr} - W_P} \\ WC \geq WC_{wt} & \rightarrow W_L = \dfrac{WC_M - WC}{WC_M - W_{wt}} \\ WC_{cr} < WC < WC_{wt} & \rightarrow \quad W_L = 1 \end{cases} \tag{S13}$$

in which

$$\begin{aligned} WC_{wt} &= 0.925\, WC_M \\ WC_{cr} &= W_P + (1 - p)(F_C - W_P) \end{aligned} \tag{S14}$$

are critical thresholds, and WC_M corresponds to saturation, F_C to field capacity, and W_P to wilting point [22], and where all soil moistures are expressed as volumetric soil water content (m$^3_{water}$/m$^3_{soil}$). The variable p is the soil water depletion factor, evaluated as [22]

$$p = 0.45 + 0.04[5 - (ET0 \times K)] \tag{S15}$$

where $ET0 = 4$ mm is the reference crop evapotranspiration, and the dimensionless coefficient K is defined by the fraction of photosynthetically active radiation (*PAR*) intercepted as

$$if\ \frac{PAR_{int}}{PAR_{up}} \leq 0.2 \ \rightarrow \quad K = 0.2$$
$$if\ \frac{PAR_{int}}{PAR_{up}} > 0.2 \ \rightarrow K = \frac{PAR_{int}}{PAR_{up}} \tag{S16}$$

PAR_{int} is the fraction of *PAR* intercepted by vegetation (equal to PAR_{up} [1-exp(-*LAI* k_i)], k_i being the extinction coefficient), and PAR_{up} is the *PAR* incident at the top of the vegetation.

Still in Equation (S8), the potential net assimilation *PNA* (g m^{-2} day^{-1} of CH_2O) is given by the following equation [22],

$$PNA = c(PGA - RC) \tag{S17}$$

in which *PGA* and *RC* have the same units of *PNA*, and *c* = 0.8. The potential gross assimilation *PGA* is evaluated as [22]

$$PGA = PAR_{int} \quad conv \quad CO2F \tag{S18}$$

where *conv* = 0.70 is a parameter, and the *CO2F* (concentration factor of CO_2) is evaluated as [22]

$$CO2F \quad = 1 + b_i \ ln\left(\frac{c_x}{c_0}\right) \tag{S19}$$

where b_i = 0.88, c_0 = 320 ppmv, and c_x = 400 ppmv.

Finally, the consumption of carbohydrates *RC* is evaluated as [22]

$$RC = TDM \ \times \ RM \tag{S20}$$

where *TDM* is the total dry matter (g m^{-2} d^{-1} of CH_2O), given by the daily sum of dry matter (*DM(n)*, Equation (S8)), and *RM* is a function of the temperature, calculated as [22]

$$RM = 3\ 10^{-5}\ T_{av}^2 - 0.0004\ \ T_{av} + 0.0022 \tag{S21}$$

in which T_{av} is the daily mean temperature.

S5. Other Outputs of IVINE

Other outputs of IVINE not used in this study for sensitivity or validation are the pre-dawn leaf water potential (kPa), the leaf area/crop weight index (m^2 kg^{-1}), the crop temperature (°C), the berry water content (%), the net short-wave and long-wave radiation (MJ m^{-2} day^{-1}), and the evapotranspiration (mm d^{-1}).

The pre-dawn leaf water potential (Ψ_{pd}, kPa) is calculated for each *i*th layer from the phenological phase of bud-burst by means of soil layer water potential (Ψ_i, considered only when larger than −1500 kPa), eventually derived from volumetric soil water content input using References [35,36] and layer root fraction (*ROOT(i)*):

$$\Psi_{pd} = \sum_i \ \frac{ROOT_i * \Psi_i}{\sum_i \quad ROOT_i} \tag{S22}$$

The leaf area/crop weight index (m^2 kg^{-1}) is an output variable simulated from the phenological phase of fruit-set by means of the ratio between leaf area index and yield. It can be a useful variable for vine management.

The simulation of crop temperature (°C) starts from the phenological phase of bud-burst and is obtained by means of a simplified energy balance. The daily crop temperature T_c is obtained by means of the minimum daily air temperature (T_{min}) and the maximum daily crop temperature (T_{cmax}):

$$T_c = \frac{(T_{cmax}+T_{min})}{2},\ T_{cmax} \text{ being } T_{cmax} = T_{max} + \frac{(\frac{RNET}{2.46} - ETR - A)}{B} \tag{S23}$$

in which the energy balance relation considers the maximum daily temperature (T_{max}), the net radiation (R_{NET}), the evapotranspiration (*ETR*, mm day^{-1}), and two parameters (*A*, *B*) where *A* is an empirical coefficient while *B* depends on plant height and soil surface roughness [46,62].

ETR is simulated from the phenological phase of bud-burst by using the reference crop evapotranspiration (*ETO*), the water limiting factor (W_L), and a coefficient (*K*) estimated on the basis of the fraction of incoming solar radiation intercepted by vine canopy [22]:

$$ETR = ETO \times W_L \times K \tag{S24}$$

Finally, the berry water content (W_{cb}, %) is simulated from the phenological phase of flowering and is obtained by means of thermal time (growing degree days, GDD_n), crop temperature (T_C), and air temperature (T_{av}) [48]:

$$\begin{gathered} W_{cb} = a * (GDD_n^2) + b * GDD_n + c - [d * (DIFF_n)] \\ DIFF_n = \sum\nolimits_n (T_c(n) - T_{av}(n)) \end{gathered} \tag{S25}$$

where the coefficients *a, b, c, d* are empirical parameters defined in the next section. Here, the berry water content is a function of thermal time (GDD_n) and the difference between crop canopy temperature (T_c) and air temperature (T_{av}). More specifically, the water content dynamic is broken into two components, one related to the berry phenological stage (thermal time) and the other to the water status of the plant. The first component describes the maximum berry water content, and the second one is linked to the difference between crop canopy and mean air temperature.

S6. IVINE Calibration

In this paper, we did not mention the results of IVINE calibration, performed in another vineyard, different from those mentioned in the "Results" section, since those data came from a private company that did not authorize us to publish their data. We wanted to underline the fact that having calibrated IVINE using a set of data different from those used for validation and sensitivity avoided any conflict of interests. In the following, we list the main IVINE parameters calibrated for cv. Nebbiolo:

- the threshold of 100 *CU* (Equation (1)) for the achievement of the dormancy exit phenological stage;
- the threshold of 8050 *GDH* (Equation (2)) for the achievement of the bud-burst phenological stage;
- the threshold of 370 *GDD* (Equation (3)) for the achievement of the flowering phenological stage;
- the threshold of 50 *GDD* (Equation (3)) for the achievement of the fruit-set phenological stage;
- the threshold of 830 *GDD* (Equation (3)) for the achievement of the beginning of ripening phenological stage;
- the threshold of 40 *GDD* (Equation (3)) for the achievement of the veraison phenological stage;
- the base temperature used in Equation (3) for defining *GDD* (set to 10 °C);
- the set of parameters used to evaluate the *LAI* in Equation (S3) (LAI_{MAX} = 0.015 m^2 vine^{-1} °C^{-1}, $PLAI_{MAX}$ = 5.0, and VEL_{MAX} = 2.2);
- the sugar content thresholds set to evaluate the achievement of some phenological stages (10 °Bx for the beginning of ripening, 12.5 °Bx for the veraison, and 25 °Bx for the harvest);
- the selection of the double sigmoid curve (Equation (S11)) to evaluate berry sugar content and the selection of the parameters E_{mg} = 0.25, E_c = 15, L_{mg} = 0.70, L_c = 11, and the number of *GDD* from flowering to the harvest stage GDD_{tot} = 1600;
- the empirical coefficients $a_4 = -2\ 10^{-8}$, $a_3 = 5.2\ 10^{-5}$, $a_2 = -0.1\ 10^{-3}$, $a_1 = 9.9\ 10^{-2}$, and $a_0 = -1.6\ 10^{-2}$, introduced in Equation (S10);
- the conversion factor *c* = 0.80 for growth respiration (Equation (S17));

- the coefficient for radiation extinction in vineyards k_i = 0.55 (in the definition of PAR_{int}, Equation (S16));
- the conversion factor from CO_2 to CH_2O ($conv$ = 0.70), Equation (S18);
- the parameters $a = -5.3\ 10^{-6}$, $b = -1.8\ 10^{-3}$, c = 93, d = 0.0458, used in Equation (S25) to define the berry water content.

S7. Slopes of Regression Trends of All IVINE Outputs

In this subsection, the complete table containing the slopes of regression trends of all IVINE outputs shown in this paper are reported for each of the 15 sites of GLDAS. Numbers in bold denote that the regression was statistically significant (at the 0.05 significance level).

Table S1. Linear regression slopes of the main IVINE variables, evaluated over the full 60-year period. Phenological stage regression slopes are expressed in JD year^{-1}, sugar content in °Bx year^{-1}, *LAI* maximum value in m^2 m^{-2} year^{-1}, and yield in kg year^{-1}. Bold values represent statistically significant trends. For some phenological phases (veraison and harvest), the stage was not reached during several years, and thus the trend was not evaluated (we have put the *** symbol in such cases).

	Bud-Break	Flowering	Fruit-Set	Beginning of Ripening	Veraison	Harvest	Dormancy Break	Sugar Content	*LAI* Max Value	Yield
01_01	**−0.2**	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.07	**0.1**	**0.1**	**−0.006**	−0.002
01_02	**−0.2**	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.08	**0.1**	**0.1**	**−0.006**	−0.003
01_03	−0.2	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.07	**0.1**	**0.1**	**−0.008**	−0.004
01_04	−0.2	**−0.2**	**−0.2**	**−0.4**	**−0.4**	−0.10	**0.1**	**0.1**	**−0.006**	−0.005
02_01	**−0.2**	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.09	**0.1**	**0.1**	**−0.003**	−0.004
02_02	−0.2	**−0.2**	**−0.2**	**−0.4**	**−0.4**	−0.10	**0.1**	**0.1**	−0.004	−0.005
02_03	−0.2	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.06	**0.1**	**0.1**	**−0.007**	−0.003
02_04	**−0.2**	**−0.2**	**−0.2**	**−0.4**	**−0.4**	−0.06	**0.1**	**0.1**	**−0.006**	−0.003
03_01	**−0.2**	**−0.2**	**−0.2**	**−0.4**	**−0.5**	−0.04	**0.1**	**0.1**	**−0.005**	−0.005
03_02	**−0.2**	**−0.2**	**−0.2**	**−0.6**	**−0.5**	***	**0.1**	**0.1**	**−0.009**	**−0.005**
03_03	**−0.2**	**−0.2**	**−0.2**	**−0.6**	**−0.5**	***	**0.1**	**0.1**	**−0.010**	−0.003
03_04	**−0.1**	**−0.2**	**−0.2**	**−0.5**	**−0.3**	***	**0.1**	**0.1**	**−0.007**	−0.004
04_01	**−0.1**	**−0.2**	**−0.2**	**−0.4**	**−0.2**	***	**0.1**	**0.1**	**−0.003**	**−0.005**
04_02	**−0.1**	**−0.2**	**−0.2**	**−0.1**	***	***	**0.1**	**0.05**	−0.001	**−0.003**
04_03	−0.1	**−0.2**	**−0.2**	**−0.5**	**−0.3**	***	**0.1**	**0.1**	**−0.004**	−0.003

References

61. Mariani, L.; Parisi, S.G.; Cola, G.; Failla, O. Climate change in Europe and effects on thermal resources for crops. *J. Biometeorol.* **2012**, *56*, 1123–1134.

62. Riou, C.; Itier, B.; Seguin, B. The influence of surface roughness on the simplified relationship between daily evaporation and surface temperature. *Int. J. Remote Sens.* **1988**, *9*, 1529–1533.