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The Effects of Tree Shade on Vineyard Microclimate and Grape Production: A Novel Approach to Sun Radiation Modelling as a Response to Climate Change

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Abstract: Climate change threatens established agricultural systems and production, driving the need for adaptation and mitigation strategies. Vitiforestry, an alternative cultivation system combining trees and shrubs in the vineyard, promotes environmental sustainability and offers a possible adaptation strategy to climate change. This work scrutinizes the impact of shading on vineyards using an Integrated Model of Vineyard Shading and Climate Adaptation (IMVSCA), supported by a system dynamics approach. This model estimates solar radiation and computes daily and annual trends of insolation, air temperature, and relative humidity to shading and its influence on vineyard growth stages. It also assesses the effects of shading-related extreme weather events and the occurrence of grapevine disease development driven by daily weather conditions and zoning adaptations. The pilot results depict the effects of tree shading on vineyards, namely the impacts of solar radiation and air temperature on vine phenology, pollination, pollen germination, fungal diseases, and the complimentary indicators of grape production and quality. Our modeling framework and findings suggest that vitiforestry could be an interesting climate change adaptation technique, providing a starting point for further studies in this scope.

Keywords: vitiforestry; climate adaptation; agroforestry systems; wine production; Douro region

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1. Introduction

Terroir is a holistic concept that incorporates environmental (e.g., climate, topography, geology–soil characteristics) and cultural (e.g., grape variety) factors that influence grape growing and wine production. Still, climate conditions are the most critical factors, which can limit grapevine growth, grape production, and quality [1,2], by changing phenology, harvesting timing, sugar content, acidity, and aromatic profiles [3,4].

The sustainability of Mediterranean crops, such as vineyards, is closely linked to their resistance and resilience to high climate variability and climate change, including extreme weather events, such as heatwaves, droughts, heavy precipitation, and high winds [5,6]. The impacts of climate change on agriculture are expected to vary, but result from the influence of atmospheric conditions on the physiological and metabolic activities of plants, their potential implications on plant growth and productivity, and weed and pest infestation, as well as socioeconomic and policy factors [7]. Thus, it is urgent to adapt agriculture to ensure food security for a growing global population, in the context of sustainable socio-economic development while tackling climate change [8].

Several authors have used indices and relationships to model and simulate the influence of current and future atmospheric conditions on viticulture [6,9,10]. However, only a handful of models integrate these tools to evaluate the influence of changing weather conditions and management strategies on viticulture productivity and quality [11,12]. Agriculture and viticulture strategies to face climate change [13–15] rely mostly on adaptation strategies to reduce the negative impacts of increasing climate variability and global warming, or to take advantage of their possible positive effects on land and farming practices (e.g., land allocation, farming system, multiple cropping systems, sowing dates, fertilization, irrigation, drainage) and crop varieties (e.g., changes in crop species, cultivars), among other things [8,16–18].

In this context, agroforestry (AF), a land use management system in which trees are grown among crops, mimicking natural ecosystems and enhancing the functionality and sustainability of the farming system, is considered a promising strategy [19]. AF is a land use practice and system, recognized by the Food and Agriculture Organization in 2015, that provides many ecosystem services and biodiversity conservation within agricultural landscapes [20]. Trees provide windbreak and shade, reducing temperature amplitudes, while deeper roots increase water infiltration and reduce water runoff and erosion [20]. AF systems have a long tradition in Mediterranean-type ecosystems, even if intensification and mechanization have contributed to their recent abandonment or conversion to intensive agriculture, pastures, or forests [21,22]. New research highlights the regulatory and support services provided by AF systems under dynamic environmental conditions including carbon sequestration in trees and soils, functional biodiversity, reduced soil erosion, increased soil fertility, retained agrochemicals and recycled water and nutrients from deeper layers, and microclimate control (radiation, temperature, humidity, wind) [23,24].

Conventional viticulture is associated with ecological and environmental issues like erosion, biodiversity loss, pest/disease dysregulation, and weather-related stress, among others [25]. Agroforestry offers a sustainable way to address these challenges, enhancing vineyard resilience and providing additional ecosystem services [26]. Despite its potential, agroforestry in vineyards has been largely overlooked, mainly due to the rise in industrial monocultures and the lack of research on tree–grapevine interactions [27].

Microclimatic interactions within vineyards, particularly shading caused by canopy management, have been studied [28–31]. These studies discuss how factors such as leaf density, the number of shoots, and row orientation influence the microclimate, optimizing solar radiation regulation to control fungi development. However, these studies do not address tree-induced shading or how trees (e.g., olive trees) may affect the vineyard microclimate. With rising temperatures and increasing numbers, the duration and severity of extreme heatwave occurrences and the use of shading, whether through canopy management or with the introduction of trees, have become increasingly important [27,32,33]. Trees in agroforestry systems offer additional benefits [27], including preventing wind damage and erosion, increasing stomatal aperture and leaf area, protecting vines from heat and frost damage, improving must quality (e.g., sugar content, whose accumulation may be delayed or halted by heat stress), and reducing viruses, fungal and bacterial diseases, and insect pests, by providing a habitat for insects' natural enemies (e.g., other insects and vertebrates). Furthermore, partial shading helps mitigate temperature spikes, preserving berry integrity and reducing the risk of quality degradation [13]. Shading practices with trees, nets, or other objects offer sustainable solutions to face the challenges posed by climate change [34]. In this scope, exploring the trade-offs of tree shade on grapevines (vitiforestry) as an adaptation to climatic impacts, while evaluating possible drifts in phenology, protection against extreme weather events, and even terroir zoning impacts, could be particularly relevant. Agroforestry is gaining renewed interest in vineyards as a sustainable solution within the

Farm to Fork Strategy, at the heart of the European Green Deal, which aims to make food systems fair, healthy, and environmentally friendly [35].

Dynamic models are especially suited to inspect the possible effects of implementing vitiforestry management options in the present and future environmental conditions [16,36,37], by incorporating variables that are difficult to tackle and integrate otherwise, thus enabling the understanding of complex processes including possible synergies and/or competition between grapevine and trees [37–39]. Eco-phenological models are a particular case of dynamic models that estimate the growth stage and phenological cycle evolution, and, for these reasons, are considered a step forward for testing the response to external drivers of perennial crops, such as grapevines [40]. They are considered one of the valuable tools, not only by researchers, but also by producers and managers, as they can help define strategies, support decision-making, and serve as warning and forecasting systems [41]. Thus, it is not surprising that in recent years, models have been developed to better understand the role of different factors in agricultural production systems, including in viticulture [42–50]. Despite the existence of all these models, there is no single tool that comprehensively models all the main processes of the phenological cycle of the vineyard and foresees the occurrence of pests and diseases within novel vitiforestry management systems.

Several modeling approaches offer valuable insights into different aspects of vineyard management and adaptation strategies, though each focuses on distinct facets of the viticultural system. For example, the IVINE model [42] was developed to study vineyard crop strategies by utilizing environmental parameters to assess phenological stages, and leaf development, yield, and sugar concentration. The VERDI model [44] addresses the water status of the biophysical vineyard system (soil–grapevine–intercrop) by focusing on radiation interception efficiency, which drives potential plant transpiration and soil evaporation, using the Total Transpirable Soil Water metric from the BISWAT model [1]. The SVAT model [45] integrates vine foliage, grassed soil, and bare soil in a three-source energy balance and mass transfer approach, aiding in the study of energy fluxes and water movement within the vineyard ecosystems. The PLASMO model [46,51] further complements these efforts by specifically modeling downy mildew (*Plasmopara viticola*) dynamics in *Vitis vinifera* L., providing information for optimizing fungicide application timing. Finally, the STICS model [47] simulates crop growth while accounting for soil water and nitrogen balances, offering insight into the interactions between plant development and resource use. While these models address important elements of viticulture from phenology and water status to disease management and energy balance, none fully integrate the climate-adaptive shading effects and mixed-crop interactions present in vitiforestry systems. A comprehensive vitiforestry model would add this crucial dimension, enabling the precise estimation of grapevine phenology and growth while optimizing practices such as pruning, irrigation, fertilization, and harvesting to boost production quality and enhance resilience to climate variability.

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To address this gap, we developed the Integrated Model of Vineyard Shading and Climate Adaptation (IMVSCA), designed specifically to model the microclimatic effects of tree shading, without delving into complex physiological or interspecies competition processes. IMVSCA integrates a set of robust submodules—originally developed by us or developed by other authors, described in previous publications and detailed in Supplementary Materials—to address the key aspects of climate adaptation in vitiforestry. Using daily meteorological data, IMVSCA estimates the daily insolation, solar radiation and photosynthetically active radiation (PAR) in the vineyard, accounting for shading effects and the sunlight filtering through tree canopy gaps. It models the temporal evolution of the vine's vegetative cycle, tracking seasonal development and key phenological stages such as budburst, flowering, veraison, and maturation. This model evaluates the probability of disease occurrence and identifies climate stress episodes that may impact vine health, including extreme weather conditions like heatwaves, frosts, storms, and droughts. It determines terroir suitability based on shading and microclimatic conditions; guiding management practices tailored to each vineyard's unique environment. While IMVSCA provides valuable support for vineyard operations and climate adaptation, we recognize that further parameterization, complementary studies, and model refinement will be necessary for guiding vitiforestry as an effective climate change adaptation strategy. Future developments will also consider water scarcity, physiological and nutrient competition processes, and the complex interactions of different species and varieties within specific local ecological and environmental conditions.

2. Materials and Methods

In the following sections, we describe the model, the data required to run it, and a set of results obtained during the verification of the modules developed and in the simulations for two contrasting climatic years. We aimed to evaluate the effects of microclimatic changes associated with the shade from trees on the vineyard, testing vitiforestry as an adaptation technique to climate change, as suggested by several authors [52–54].

2.1. Model Overview

The IMVSCA (Figure 1) comprises four modules, namely the Light–Shadow Module (LSM), the Phenological Module (PM), the Zoning Module (ZM), and the Illness Module (IM). The LSM includes a shading model developed by the authors and presented in this work. It also results from the integration of the physical and semi-empirical models developed by other researchers, duly cited throughout the model explanation in Supplementary Materials. These modules were implemented to simulate the impact of shading on vineyard microclimates, phenology, and disease outbreaks through an integrative approach.

The LSM includes three submodules: (i) Sunrise–Sunset, which estimates the time of the sunrise and sunset for a specific location and Julian day; (ii) Tree–Shadow (TS), which estimates the effect of the tree's shadow, namely on the daily sunshine duration on a grapevine, based on the incident the solar radiation passes around, over and under a tree crown; and, (iii) Light–Orchard, which computes the active photosynthetic radiation that passes around tree crowns, based on the vineyard configuration and proportion of the vineyard floor that is shaded by trees (not used in our simulations). Both of the light submodules consider the dimensions, position, and distance between the tree location and the grapevine as well as the slope and exposure of the study site.

The PM is a cluster of robust rules of grapevine phenological timings for a large number of grapevine varieties, based on the meteorological variables and parameters that might affect yields. The ZM includes a set of useful and widely used viticulture zoning bioclimatic indices to assess the suitability of a particular study region for the cultivation of grapevines. This set includes the Geoviticulture Multicriteria Climatic Classification System by Tonietto and Carbonneau [55] to classify vineyard areas on a macroclimatic scale, using the Monthly Dryness Index, the Heliothermal Index of Huglin [56], and the Cool Night Index [57]. Additionally, it includes the Cool Night Quality Bioclimatic Index [58] to quantify the mean thermal amplitude during maturation, the Hydrothermal Index of Branas [59] to assess the mildew infection risks, the Growing Season Suitability Index [60], and the Growing Season Precipitation Index [61]. This module also employs the Tonietto algorithm to estimate the Potential Sugar Content Index [57], with the Hydrologic Balance calculated using the Monthly Dryness Index. ZM also identifies the critical phases of the vegetative cycle and guides the application of spraying against diseases and pests in the vineyards. The IM includes the powdery mildew (fungal pathogen *Uncinula necator*) and downy mildew (pathogen *Plasmopara viticola*) submodules, which can detect favorable weather conditions for the outbreak of relevant fungal diseases. The IM is supported by qualitative and empirical indices, triggering early warnings and alerts (not tested or validated here). The model was initially conceptualized using STELLA (version 9.0.3.1, isee Systems, Inc., Lebanon, PA, USA) software, complemented with modules (e.g., Sunrise–Sunset, Light-Shadow, Light–Orchard) in Python (version 2.7). A detailed description of the modules and submodules is provided in Supplementary Materials.

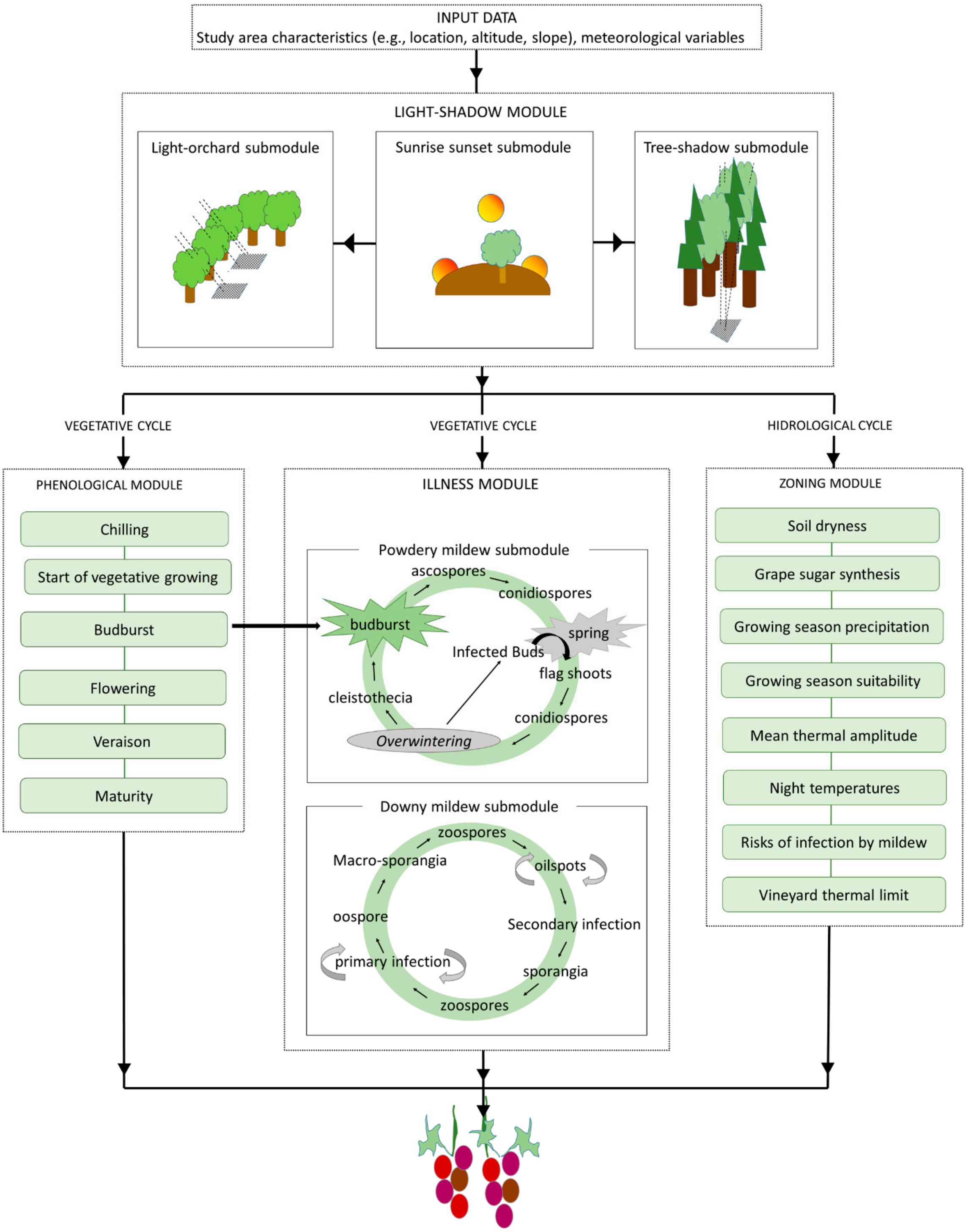

Figure 1. The Integrated Model of Vineyard Shading and Climate Adaptation (IMVSCA) scheme, with the logical sequence of its modules. The Light–Shadow Module consists of three submodules: Sunrise–Sunset, Light–Orchard, and Tree–Shadow.

2.2. Description of IMVSCA Modules and Submodules

The PM, ZM, and IM modules of the IMVSCA were based on several models and indices previously developed for viticulture and winemaking. A detailed description of these modules and the references supporting them can be found in Supplementary Materials. The TS submodule was developed by the authors for this study and, for that reason, is detailed in the following lines.

2.2.1. The Sunrise–Sunset Submodule

This submodule converts the Gregorian calendar date into the Julian calendar date using the formulation of Duffett–Smith [62] and computes the local hours of sunrise and sunset for any solar declination and latitude using the formulation of Nasrin et al. [63]. In detail, this module determines, based on the Julian date, the mean solar time, the solar mean anomaly, the equation of the center, the ecliptic longitude, the solar transit, the declination of the sun, the hour angle and, finally, the actual Julian date of the sunrise and the sunset. Then, the submodule converts the Julian date of sunrise and sunset into a calendar date [62,64], and the decimal part of the day is multiplied by 24 to give the hour and seconds of sunrise and sunset.

2.2.2. The Tree–Shadow Submodule

This submodule uses the methodology of Hu et al. [65] to estimate the solar height θ, based on the solar declination δ, the local latitude ϕ (north positive), and the hour angle ω, and calculates the solar azimuth ψ. This submodule calculates the eccentricity correction factor of the Earth's orbit and E_0, from the day angle Γ. This module uses the δ estimated in the Sunrise–Sunset module.

The effect of the tree shadow on the air temperature near the grapevine depends on many factors, including the shape and size of the grapevine and the tree, the distance between the vine and the tree (d_{VT}), the position of the sun, namely, the solar azimuth (ψ), and the solar height (θ) angles, which vary daily and throughout the year (Figure 2a,b).

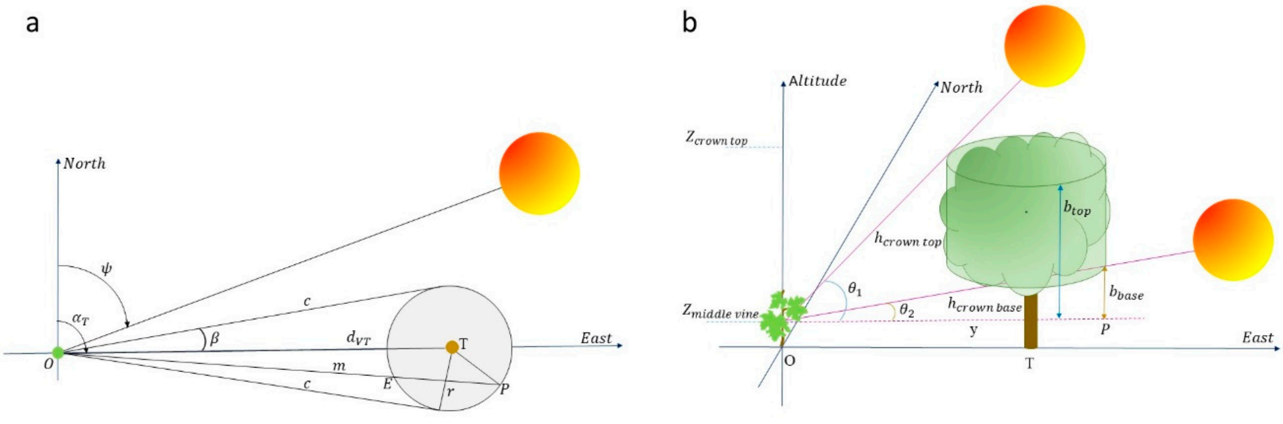

Figure 2. Description of the shadow effect of a tree on a grapevine according to the (**a**) azimuthal and (**b**) zenithal movement of the sun. The tree has a cylindrical trunk of negligible diameter, a cylindrical crown with a radius r and a height $h = h_{crown\ top} - h_{crown\ base}$. Without losing generality, in the case illustrated in the figure, the grapevine is located at point O and the tree at point T to the east, and at a distance (d_{VT}) from the grapevine. On panel (**a**), ψ represents the azimuthal angle of the sun, which changes from sunrise to sunset, α_T is the constant azimuth angle of the tree trunk, and β is the shadow angle defined between the line segments $\overline{OT}$ and the tangents c to the projection of the crown on the horizontal plane. On panel (**b**), θ is the solar height angle, which also changes in time, and θ_1 and θ_2 are the height angle of the tree crown top and bottom, respectively.

To assess and quantify the effect of the tree shade we considered the following: a tree with a cylindrical trunk of a negligible diameter, and a cylindrical crown with a radius r and a height ($h_{crown\ top} - h_{crown\ base}$). The model can also estimate the effect of trees with other shapes and sizes. The shadow angle β (Figure 2) can be computed as

$$\beta = \arccos(c/d_{GT}) \tag{1}$$

where using the Pythagorean theorem,

$$c^2 = {d_{GT}}^2 - r^2 \tag{2}$$

So, according to the azimuthal movement of the sun, the necessary condition for tree shade is

$$\alpha_T - \beta < \psi(t) < \alpha_T + \beta \tag{3}$$

However, even in these conditions, the sun can directly illuminate the grapevin, if it has an angular height less than the height of the base of the canopy ($\theta(t) < \theta_2$) or greater than the height of the top of the tree canopy ($\theta(t) > \theta_1$), i.e.,

$$\theta_1 < \theta(t) < \theta_2 \tag{4}$$

which is the necessary condition for the tree to shade the grapevine according to the zenithal movement of the sun. So, Equations (3) and (4) are the necessary conditions for the tree to shade the grapevine. The potential sunshine duration (PSD) during a period D at point P can be computed as,

$$PSD = I.\sum_{t=0}^{D} c(t) \tag{5}$$

where t is the time step interval varying during D, I is an interval (considered 1 h in our study), and

$$\begin{cases} c(t) = 0, \text{ before the sunrise and after the sunset} \\ c(t) = 1, \text{ when the grapevine is in the sun during the entire time step} \\ c(t) = 0.5, \text{ when the grapevine is in shadow during the entire time step} \\ 0.5 < c(t) < 1, \text{ when the grapevine is partially in shadow during the time step} \end{cases} \tag{6}$$

The value of $c(t)$ is 0.5 when the grapevine is in shadow and not zero to account for the diffuse radiation. In this version, we assume a constant value for simplicity. However, $c(t)$ varies with the distance between the vine and the tree and the cloud cover, so it can be modeled to account for these factors.

The effect of the tree's shade on the vine translates into a reduction in temperature to the shaded temperature value, evaluated from

$$T_{shade} = \frac{1}{2}(H/A_{HG}H_0)^2 + T_{min} \tag{7}$$

where H_0 is the daily extraterrestrial radiation, H is the daily global radiation estimated from the sunrise to the sunset with the Angstrom–Prescott model [66], T_{min} is the daily minimum air temperature, and the recommended value of the empirical coefficient A_{HG} is 0.16 for inland regions, or 0.17 for coastal regions. Please see Supplementary Materials for further details. Finally, it is important to mention that the daily global radiation and, consequently, the relative humidity and mean air temperature in the grapevine were estimated assuming a uniform distribution of the radiation during the daily sunshine duration.

2.3. Study Area

To calibrate and perform a preliminary assessment of the IMVSCA, we had considered the following: (i) a vineyard located near Pinhão village (41°10′12′′ N, 7°32′60′′ W) at 130 m of altitude, in the Douro Demarcated Region (Portugal) [67]; (ii) the grapevine variety Touriga Franca, which is most extensively planted in the region [68–70]; and, (iii) olive trees, which are traditionally used in this region to limit vineyard fields, as a shade tree [71]. The height (130 m a.s.l.), slope (35.60°), and aspect (245.67°) of the ground were determined using the image processing tools of ArcGIS 10.5 (https://www.esri.com/en-us/home, accessed on 8 January 2024), using a topography raster map of Continental Portugal with a 25 m resolution [72]. To simplify the performance evaluation process, a vineyard on a horizontal surface was considered; that is, the slope and aspect were not considered in our preliminary assessment.

This region has a Csa type of climate, characterized by an average temperature in the coldest months between 0 and 18 °C with a dry summer and an average air temperature above 22 °C in the hottest month, which is August, followed very closely by July [73,74]. In Pinhão and the 1981–2010 climatological standard normal period [75], the average number of days with a maximum air temperature (T_{max}) $T_{max} \geq 30$ and $T_{max} \geq 35$ are 85.2 and 33.3, respectively. The maximum and minimum number of days with $T_{max} \geq 30$ and $T_{max} \geq 35$ are 134 and 49, respectively. These results reveal high interannual climate variability, but also the occurrence of a high number of days with harmful weather conditions for grape growing and physiology. The influence of weather on grapevine phenology is well-documented in our case study, i.e., both grapevine variety and region [76–80]. In addition, the Portuguese Meteorological Office (Portuguese Institute of Sea and Atmosphere, IPMA) has a weather station in Pinhão, which allows access to local meteorological observations, where our idealized experiment was designed and analyzed.

2.4. Meteorological and Other Environmental Data

The input data to run the modules included the daily time series of several meteorological variables for two extended yearly periods, defined from September of one year to October of the next year, to comprise the grapevine's complete phenological and hydrological cycles. The meteorological variables included were as follows: (i) the accumulated precipitation, a 2 m dew point, the mean, maximum and minimum air temperature, and a 10 m wind speed from the weather station of Pinhão; (ii) the surface air pressure and surface net radiation of the grid point of the ECMWF ERA-Interim reanalysis dataset [81,82], closer to the weather station of Pinhão.

The model was tested for two periods, 1981–1982 (hereafter 1982) and 2004–2005 (hereafter 2005), because of their contrasting weather conditions (Figure 3).

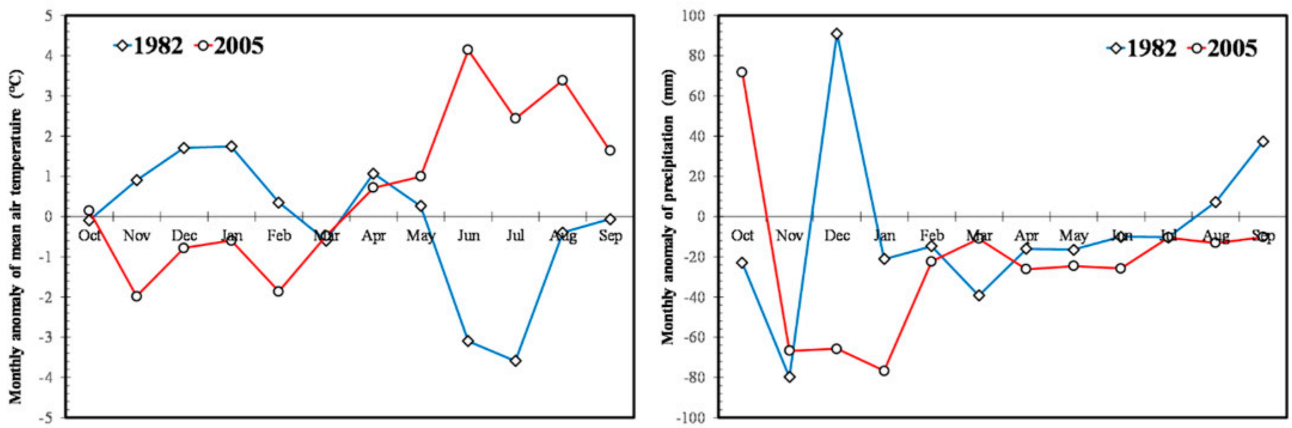

Figure 3. The monthly anomaly of the mean air temperature (**left panel**) and the precipitation (**right panel**) in the weather station of Pinhão for the years 1981–1982 and 2004–2005 (an anomaly is the difference between the monthly mean for a specific month of a specific year and the climatological normal for that month).

The year 1982 was characterized by an unusually hot winter, while the crucial period for the development of the vineyards (from June to August) was unusually cold. Contrarily, 2005 had an unusually cold winter, while the crucial period for the development of the vineyard was unusually hot. Concerning the mean air temperature, the two years were only approximately similar (from March to May). The precipitation in these two years was relatively below average during most of the vegetative cycle, except in August and September of 1982, when the above-average precipitation occurred.

To understand the selection of these two years used to test the model, it is important to mention that the average air temperature in the grapevine development period has increased in the last few decades. Thus, 1982 corresponds to a decade with a lower average air temperature and later phenological phases while 2005 represents a decade with a higher average air temperature and earlier phases. This is in line with the findings of previous studies for the same region [76], reporting increasing trends in the minimum, mean and maximum air temperature from April to September, as well as on some indices (e.g., HI and CNI). This result is in good agreement with the results of several studies that suggest climate change is observable today in relatively short and recent study periods, as well as that its effects are already being felt, and adaptation measures to face climate change are already needed [83].

2.5. Model's Performance

As the model results derive from the integration of the empirical, semi-empirical, and physical models and indices validated and presented in previous publications, it can be accurately simulated using observed data and site-specific information (e.g., latitude, altitude, slope, exposure). However, the models within the TS submodule were validated as a cohesive set in this study to evaluate the effect of tree shade on microclimatic conditions. To validate the TS module and facilitate the interpretation of the results of the evaluation of the effects of tree shade on the microclimate of the vine, we considered the following: (i) a single Touriga Franca grapevine in a horizontal terrain (i.e., without slope and aspect) to prevent these features from affecting the impact of the relative position of the tree to the grapevine; (ii) simulations with just one tree each time, located at one of the cardinal points to the grapevine and at distances of 3 m and 2.5 m, which are commonly observed between vineyard rows and marginal olive trees in this region; (iii) a tree with a cylindrical crown shape without gaps, a negligible trunk width compared to the size of the crown; (iv) the height of the olive trees and the Touriga Franca grapevine set as 4 m and 1.50 m, respectively, with the olive tree canopy base height set to 1.5 m; (v) when the tree is located between the sun and the grapevine, solar radiation can pass freely just under or over the crown; and (v) the years of 1982 and 2005. The simulations with the tree located in the north can be considered as a benchmark, since this tree never casts shade on the grapevine. Thus, the results obtained with the simulations with the trees located in the other positions can be compared to those obtained from the tree to the north and the effect of the shade can be evaluated. A comparison between the results obtained with the observed data and those simulated for the tree located in the north allows us to assess the TS submodule's performance.

The influence of the tree shade (assessed with the TS submodule) on the PM was tested using the two contrasting years presented (1982 and 2005), and assessed by comparing them with the results of Real et al., 2015 that computed the mean dates of the major periods of the phenological phases for the grapevines grown in the Douro Valley during 1980–2009, and the results of Sousa [77], which described the average observed dates of the major phenological phases for a vineyard of the Touriga Franca variety for the 2001–2012 period in the *Quinta de Santa Bárbara* (QSB, 41°10′21.209″ N, 7°32′58.452″ W). Furthermore, it enables an additional comparison to the obtained dates of the phenological phases of the Association for the Development of Douro Viticulture (*Associação para o Desenvolvimento da Viticultura Duriense*, ADVID) results [84].

3. Results and Discussion

3.1. Assessment of the PM Submodule

To evaluate the performance of the PM, the dates of the main phenological phases of the vine were estimated by the module for the years 1982 and 2005, with and without the effect of tree shadow. The results were graphically represented (Figure 4), together with the average periods of the phases estimated for the Douro Valley region [85], and observed in two nearby locations: Peso da Régua [84] and the QSB located in Pinhão [77].

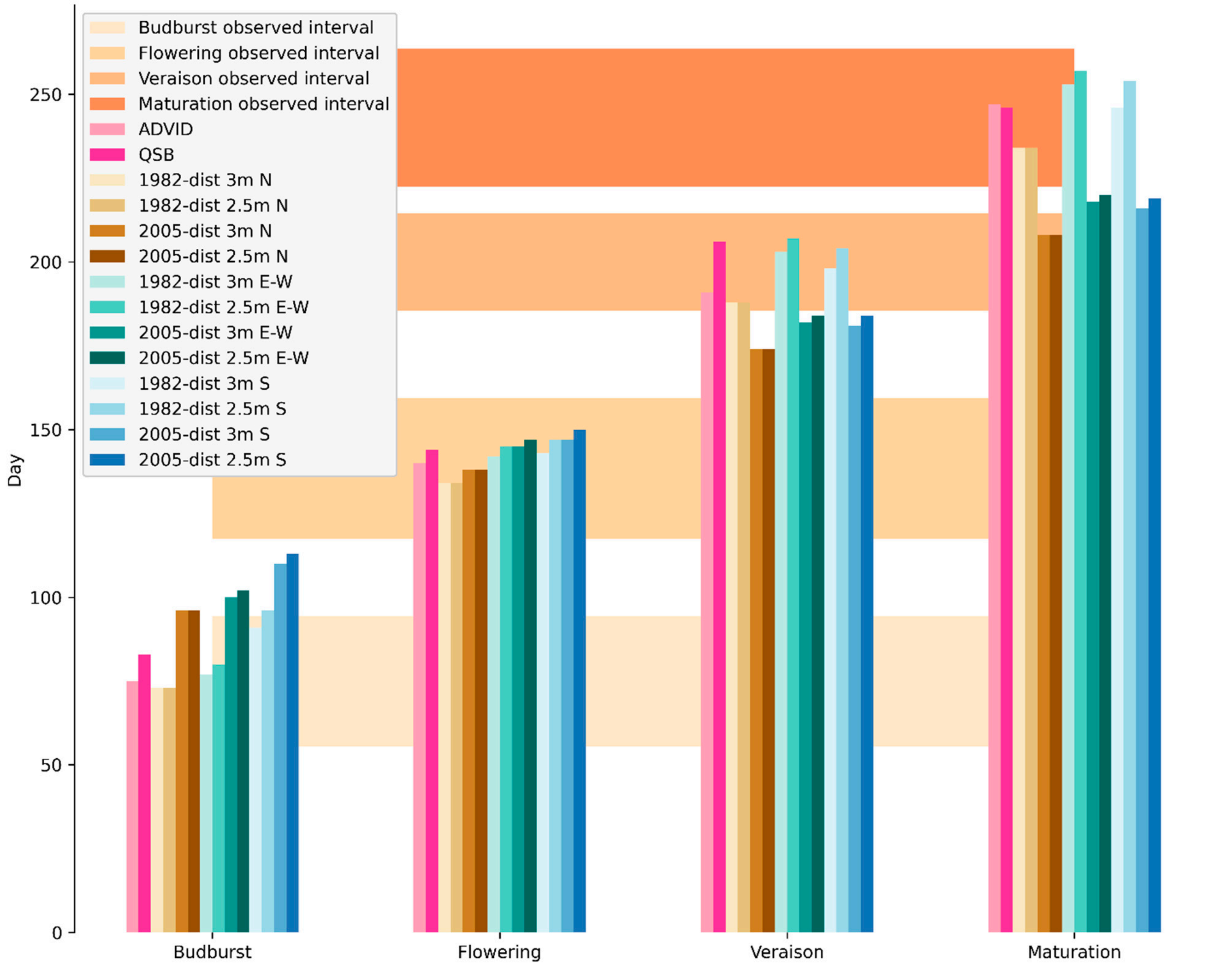

Figure 4. Periods (maximum and minimum dates) of the major phenological phases of the grapevines grown in the Douro Valley (beige horizontal bars), computed for the 1980–2009 period (Real et al., 2015), and the average dates of the same events obtained from the observed phenological dates in the city of Peso da Régua (light pink vertical bars) provided by the Association for the Development of Douro Viticulture (Associação para o Desenvolvimento da Viticultura Duriense, ADVID) (ADVID 2012), and in the Quinta de Santa Bárbara (QSB) (dark pink vertical bars), located in Pinhão (Sousa 2014), and simulated by the PM, using data from the weather station located in Pinhão, for the Touriga Franca variety, years 1982 and 2005, and considering the shadow effect of trees placed at the distances of 2.5 m (T2.5m) and 3 m (T3m) from the grapevine, north, east, south, and west of the grapevine.

The average periods of the phenological phases in the Douro Valley region (beige horizontal bars in Figure 4) were as follows: budburst begins in the last week of February (February 25, day 56) and ends in the first week of April (April 4, day 94); flowering starts in the last week of April (April 28, day 118) and lasts until the first week of June (June 8, day 159); the veraison initiates in the first week of July (July 5, day 186) and terminates in the first week of August (August 2, day 214); and, lastly, maturity lasts from the second fortnight of August (August 11, day 224) to the third week of September (September 20, day 263) [85].

The average dates of the phenological phases for the two specific locations close to the study site (Peso da Régua and Pinhão) were within the average periods of the phenological phases in the Douro Valley region. However, the difference between the dates for the two locations is not constant across the phenological phases. The first three phases tend to occur later in the QSB (8 days in budburst, 4 days in flowering, 15 days in veraison) except for grape maturity (which occurs one day earlier). To evaluate the comparative analysis carried out, it is important to consider that we were not able to find grapevine phenology data for a long period for the study site; QSB data refer to the period 2001–2012, but we do not know the period of the data used by ADVID; the ADVID records come from a larger area and represent an average value that incorporates several varieties, unlike the QSB data that refer only to the Touriga Franca variety.

Focusing on the results obtained for the tree placed to the north of the vineyard (without the tree shadow effect), it is clear that the PM simulations reflect the climatic characteristics of the two years. Until May, the first two phenological phases (budburst and flowering) occurred earlier in 1982, while the last two phases (veraison and maturity) occurred earlier in 2005 as a result, and occurred in line with the mean air temperature annual cycle in these years (Figure 3). However, although the PM simulations for 1982 are within the observed ranges for the Douro region, the same is not true for the 2005 simulations. The simulated veraison and maturity for 2005 occurred much earlier than the observed average range, which is a result of the extreme climatic characteristics of this year. In 2005, and concerning the mean phenological phases' periods defined by [85], the budburst occurred near the end of the correspondent mean period, while the veraison and maturity occurred, respectively, 12 and 15 days before the respective mean periods. These results are due to significative air temperature anomalies, namely negative ones (almost −2 °C) in February, which promoted the delay in the budburst, and positive ones (between 2 °C and 4 °C) from the end of the spring and throughout the summer season (Figure 3), which promoted the advance of the emergence of veraison and the maturation of the grapes (Figure 4).

In summary, the results of the PM for the Touriga Franca grapevine in the years 1982 and 2005 suggest the model's ability to mimic phenological phases, while capturing the effects of contrasting weather conditions, in line with the results from other phenological cycle modeling solutions [86]. In 1982, a relatively warm winter, an approximately normal spring, and a cool summer resulted in the simulated normal dates of all the phenological phases. In 2005, a cold winter, a normal spring, and a hot summer justified the significant delay, namely in the budburst, and the significant anticipation of the last vegetative phases of veraison and maturity. These alterations in the periods of the phenological phases forced by weather conditions are in agreement with the results of other studies [50,70,87,88].

3.2. Assessment of the Tree–Shadow Submodule

The TS submodule simulation results include the potential insolation and shade hourly periods when the trees are positioned at different distances of 2.5 m (T2.5m) and 3 m (T3m) to the north, east, south, and west of the grapevine. We present the daily global radiation for the 15th day of January, April, July, and October (Table 1) as these days are representative of the average conditions across the four seasons of the year. They correspond to the days in the middle of each season of the year, defined here as the following usual sets of three months: winter = December, January, and February; spring = March, April, and May; summer = June, July, and August; and, autumn = September, October, and November.

Table 1. Daily global radiation over the grapevine on the 15th of January, April, July, and October of 1982, simulated by the Tree–Shadow submodule, considering the shadow effect of a tree positioned at different locations (north, east, south, and west) and distance to the grapevine of 3 m (T3m) and 2.5 m (T2.5m).

	Daily Global Radiation (MJ m^{-2} day^{-1})					
Tree distance	T3m			T2.5m		
Tree location	North	West, East	South	North	West, East	South
January 15th	7.52	7.43	5.86	7.52	7.22	5.76
April 15th	20.55	18.56	18.82	20.55	18.32	18.19
July 15th	27.56	24.70	26.53	27.56	24.45	25.66
October 15th	13.75	13.05	11.71	13.75	12.75	10.57

To evaluate the performance of the TS submodule and understand the influence of the shadow effect on the grapevine, it is important to highlight the following: as would be expected from the annual movement of the sun in the mid-latitudes of the northern hemisphere, the tree placed to the north does not shade the vine; the tree closer to the vine causes longer periods of shade; the cyclic effect of the tree placed south of the vine is characterized by a maximum in the winter and a minimum in the summer; the effect of the trees placed east and west is symmetrical concerning the solar noon; and the shading effect of these trees are characterized by seasonality in opposition to the phase to the tree placed to the south (maximum shade in summer and minimum in winter). Also, the effect of the tree placed to the east and west being identical derives from the temperature being assessed based on radiation and not considering the thermal inertia that leads to afternoons that are hotter than the mornings. The effect of the shadow should not be the same during the colder mornings or the hotter afternoons. All these features were evident in the TS submodule simulation results of the hourly and daily potential insolation in the grapevine as a function of the apparent movement of the sun and the possible shade caused by a tree positioned to the north, west, south, and east at distances of 2.5 m and 3.0 m of the grapevine. The daily global solar radiation simulated by the TS submodule for any of the locations of the tree to the grapevine presented minimum values in January, maximum values in July, and intermediate values in April and October (Table 1).

These results are in line with the temporal variability of the global horizontal irradiance (GHI), which is the total solar irradiance (TSI) on a horizontal plane at the surface of the Earth. The TSI measures the solar power over all the wavelengths per unit area perpendicular to the incoming sunlight incident on the Earth's upper atmosphere. The GHI is the sum of the direct normal (considering the solar zenith angle, θ) and diffuse horizontal irradiance ($GHI = DNI \times \cos(\theta) + DHI$).

The DHI is the solar radiation at the Earth's surface scattered by the atmosphere, and the DNI is equal to the extraterrestrial irradiance above the atmosphere minus the absorption and scattering by the atmosphere [89]. These losses vary with the time of day (the length of the light path through the atmosphere depending on the solar height), the atmospheric composition, and the cloud cover. The TSI and, consequently, the GHI vary in time at different scales, slowly over decennial and longer scales due to changes in solar activity and changes in the Earth's orbital parameters around the sun [90,91]. Additionally, they vary throughout the year because the distance from the Earth to the sun varies as the Earth travels through its elliptical orbit, passing through perihelion and aphelion. Over the course of a year, these variations are negligible when compared to those due to the spherical shape and tilt of the Earth's axis, associated with the seasons that explain the annual cycle of global radiation [92–94].

The simulated daily global solar radiation values for the trees placed to the west/east and south of the vine were lower than those obtained for the trees placed in the north, with no shading effect. The decrease was greater for the tree placed closer (T2.5m) than for the tree placed further away from the vine (T3m). These differences in the results allow us to evaluate the effect of the shade caused by trees placed in different positions and distances from the grapevine. In the case of T3m, the decrease in the sum of the four values of daily global solar radiation was −8.1% in the case of the tree placed to the west/east and −9.3% in the case of the tree placed to the south. The corresponding values for T2.5m were −9.6% and −13.3%, respectively. In the case of T3m, and on each of the indicated days, the decrease in the global daily solar radiation varied from a minimum value of −1.2% in January to a maximum value of −10.4% in July, in the case of the tree placed to the west/east, and from −3.7% in July to −22.1% in January, in the case of the tree placed to the south. The corresponding values for T2.5m were, respectively, −4.0% and 11.3% for the tree placed to the west/east, and −6.9% and 23.4% for the tree placed to the south.

The differences in the global daily solar radiation are easily explained by the apparent movement of the sun throughout the day and the predicted possibility in the model that solar radiation could pass under and over the tree canopy. This apparent movement of the sun, from sunrise to sunset, can be decomposed into an azimuthal movement in which the sun moves from east to west through the south and a movement in the altitude, in which the height of the sun increases in the first part of the day and decreases in the second part of the day, during its movement. On the other hand, the higher results for T2.5m than for T3m are a consequence of the greater shading effect caused by the nearest tree.

The results obtained for the mean air temperature (Table 2) are in good agreement with the patterns and trends observed in the daily global solar radiation (Table 1), mainly because the mean air temperature is estimated by the TS submodule based on the solar radiation and the minimum temperature observed at the site, following the models of Angstrom–Prescott [66] and Hargreaves [95]. For T3m, the average of the differences in the mean air temperature for the four days was −6.4% for the tree placed to the west/east and −9.6% for the tree placed to the south. The corresponding values for T2.5m were, respectively, −7.9% and −13.0%. In the case of T3m, and on each of the indicated days (Table 2), the decrease in the mean air temperature varied from a maximum value of −0.13 °C in January to a minimum value of −1.76 °C in July, in the case of the tree placed to the west/east, and from −0.65 °C in July to −2.06 °C in January, in the case of the tree placed to the south. The corresponding values for T2.5m were, respectively, −0.42 °C and −1.91 °C for the tree placed to the west/east and −1.19% and −3.7 °C for the tree placed to the south.

Table 2. Daily mean air temperature near the grapevine on the 15th of January, April, July, and October of 1982, simulated by the Tree–Shadow submodule, considering the shadow effect of a tree positioned at different locations (north, east, south, and west) and a distance to the grapevine of 3 m (T3m) and 2.5 m (T2.5m).

	Daily Mean Air Temperature (°C)					
Tree distance		T3m			T2.5m	
Tree location	North	West, East	South	North	West, East	South
January 15th	10.03	9.90	7.97	10.03	9.61	7.86
April 15th	13.30	12.05	12.21	13.30	11.90	11.83
July 15th	21.46	19.70	20.81	21.46	19.55	20.27
October 15th	15.82	15.08	13.79	15.82	14.78	12.79

3.3. Assessment of the Influence of the Tree Shade on Grapevine Phenology

The effect of tree shade on the stages of the vegetative cycle of the vine can be evaluated by comparing the dates of the main phenological phases under the effect of shade and with the observed mean dates (in the Douro Valley [85], in the city of Peso da Régua [84] and the QSB, located in Pinhão [77] (Figure 4). In short, the results reveal that the presence of trees leads to a delay in all phenological phases. This delay tends to increase throughout the veraison and maturation period, especially in the years with below-normal air temperatures during those periods, such as 1982 (Figure 3). The delay is also longer when the tree is closer to the vine. In the first two phases (Budburst and Flowering), the effect of the tree placed south of the vine is greater than the trees placed in the east and west, but the order is reversed in the last two phases (veraison and maturation). This is a consequence of the variation in the height of the sun throughout the year in the period around solar noon. At the beginning of the year, the sun is low enough for the tree placed in the south to provide significant shade over the vine. In the summer, the sun is much higher—higher than the tree—which allows it to illuminate the vine and lessen the tree's shadow effect. However, even though the sun is highest in the summer around noon, it remains relatively low in the periods close to sunrise and sunset, when the trees placed east and west of the vine exert their shading effect. These results of the PM are in line with those of the TS submodule (Tables 1 and 2). Comparing the results for 1982 and 2005, it is also important to point out that the delay is greater in 2005, for the first two phases, and 1982, for the last two phases.

The influence of the shade effect of the trees placed in different positions around the vine and the different climatic characteristics of the two simulation years is evident in the assessment of the optimum weather conditions for the grapevine pollination and germination of the pollen for the years 1982 and 2005 (Figure 5). The most evident features of the simulations made for the pollination and germination of the pollen phases are the significant difference between the number of days of optimum weather for each process for the years 1982 and 2005, independent of the influence of the tree's location. While, in 1982, there were almost exclusively days with optimal conditions for pollination, in 2005, there were a large number of days with unfavorable conditions for germination and just a few days with optimal conditions for pollination.

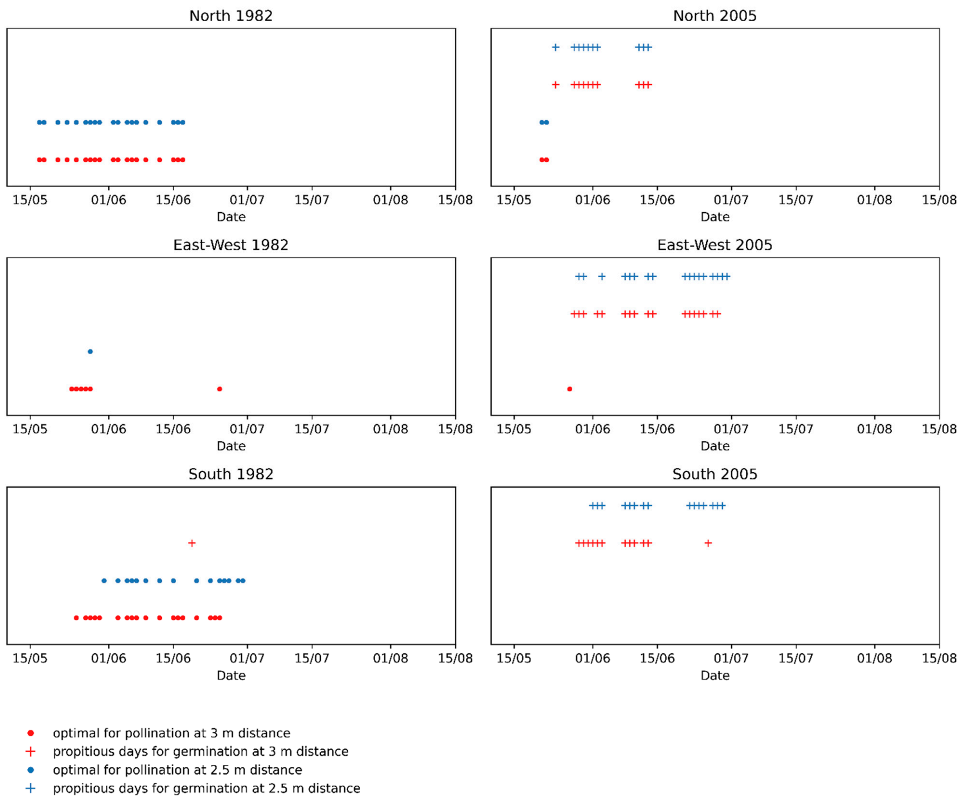

Figure 5. Simulation of the days with optimum weather conditions for the grapevine pollination and germination of the pollen for the years 1982 and 2005, under the influence of the trees located at a distance from the vineyard of 2.5 m and 3 m positioned at the north, west or east, and south of the grapevine.

These results are a consequence of how these days are identified (please see Section 2.2.2) and the distinct daily weather conditions during the periods of pollination and germination (Figure 3). Fertilization success, which includes a sequence of events (pollination, pollen germination, and pollen tube growth), is very dependent on meteorological conditions [96]. High air temperature at the end of the winter and adequate relative humidity (<65%) induce the successful transfer of pollen [97]. Precipitation can disrupt pollination and hinder the reproductive efforts of flowering grapevine [98]. Air humidity is also important because (i) an excessively high temperature and low air humidity (<45%) impair normal flowering; (ii) hot and very dry conditions are essential for dehiscence to occur; and (iii) dry, warm, and sunny days favor aerial pollen dispersal; but, (iv) very dry and windy conditions dry out the stigma and prevent pollen from sticking to it [99]. Pollen germination and pollen tube growth in grapevines are temperature-sensitive processes, with the maximum performance in the air temperature range of [25 °C, 30 °C]; but, temperatures of less than 15 °C impede pollen tube growth too much to allow fertilization before the eggs degenerate while germination ceases at temperatures <10 °C and >35 °C [96,100]. These insights help to explain the optimum weather conditions for grapevine pollination in 1982 and germination in 2005. In 1982, the precipitation anomaly was negative throughout the usual pollination period, but the air temperature was slightly above average in May and the relative humidity was normal under the trees, which explains the optimal weather conditions for pollination. On the other hand, the negative air temperature anomaly during the germination period explains the non-optimal weather for this process in 1982. In contrast, the high-temperature anomaly (4 °C), low precipitation anomaly and, consequently, very dry environment under the tree in June 2005 created optimal conditions for pollen germination processes but not for pollination [99].

The influence of the tree shade on the grapevine also had effects on the pollination and germination of pollen, as depicted by the simulations' pattern for the years 1982 and 2005 (Figure 5). Pollination and germination occurred sooner in the case of the tree placed at the north (no shade reference case) and later when the trees cast shade over the vine.

Additionally, the shade led to a decrease, more significant for the tree placed to the west/east than to the south, in the number of days with optimal conditions for pollination in the year 1982, and, an increase, more significant for the tree placed to the west/east than to the south, in the number of days with optimal conditions for germination in 2005. These results agree with the thermal and hydric conditions of these years (Figure 3), namely the mean air temperature anomaly in June, which was negative in 1982 and positive in 2005. Although the year 1982 presented several days with atmospheric conditions for optimal pollination, when the tree was placed north or south of the grapevine, the number of days with such conditions decreased significantly when compared to when the tree was located east or west of the grapevine, because of the higher shade effect.

The presence of trees may change the effects of extreme weather events that might cause damage to the vineyards, by modulating the microclimatic conditions. A higher number of grape sunburns and much higher values of air temperature above the sunburn temperature threshold were simulated for 2005 than for 1982 (Table 3), clearly associated with the different climatic characteristics of these years (Figure 3).

The warm summer of 2005, when the mean air temperature anomaly was significantly above normal (4.1 °C in June, 2.4 °C in July and 3.4 °C in August) explains the high number of grape sunburns in these months, as suggested by Costa et al. [101]. The obtained results reveal the ability of the trees' shade to change the effect of the extreme temperature of the air. The T2.5m placed in the west/east was able to prevent the occurrence/effects of the only air temperature extremes in 1982, but both of the tree placements were able to prevent grape sunburns in 2005. Following the previous results, the protective capacity of the effects of high air temperature events on the vine was greater in the tree placed at west/east (two of the three events) than at the south (one event). The model is also able to detect white frost, freeze frost, black frost, and meteorological frost; however, the simulations for these two years did not lead to the identification of any of these extreme events.

Table 3. Extreme events that might damage the grapevine for 1982 and 2005, under the influence of the trees located at a distance of 3 m (T3m) and 2.5 m (T2.5m) positioned at the north, south, and the west or east (west–east). The date of the grapevine berry sunburn and the value of the air temperature above the sunburn threshold is also provided.

Year	1982					
Tree distance	T3m			T2.5m		
Tree location	North	West–East	South	North	West–East	South
Date of grape sunburn	08/08	-	08/08	08/08	-	-
Value higher than sunburn threshold (°C)	1.5	-	1.5	1.5	-	-
Year	2005					
Tree distance	T3m			T2.5m		
Tree location	North	West–East	South	North	West–East	South
Date of grape sunburn	16/06 11/07 18/07 02/08 04/08	11/07 02/08 04/08	16/06 11/07 18/07 02/08 04/08	16/06 11/07 18/07 02/08 04/08	11/07 02/08 04/08	11/07 02/08 04/08
Value higher than sunburn threshold (°C)	1.5 0.5 3.0 1.0 4.0	0.5 1.0 4.0	0.5 3.0 1.0 4.0	1.5 0.5 3.0 1.0 4.0	0.5 1.0 4.0	0.5 1.0 4.0

The bioclimatic indices that do not depend on the average temperature were calculated with the observed data from the IPMA, and helped to complement and agree with the climate characterization of these years, made earlier, in Section 2.4. For example, $GSP(1982) = 182.1$ mm and $GSP(2005) = 80.1$ mm, confirming (Figure 3) that the rainfall in the growing season (April to September) in both years was less than normal ($\overline{GSP} = 190.3$ mm), although 2005 was significantly drier ($GSP(2005) = 0.42 \times \overline{GSP}$) than 1982 ($GSP(1982) = 0.96 \times \overline{GSP}$). On the other hand, the summer of 2005 was hotter than in 1982 (Figure 3), which helps explain why the CNI values for 2005 ($CNI(2005) = 17.4$ °C) were higher than for 1982 ($CNI(1982) = 14.9$ °C). In addition, the $MTAS(1982) = 13.7$ °C $>$ $MTAS(2005) = 12.4$ °C, which means that the high average temperature in September 2005 was due to a greater increase in the minimum temperature than in the maximum temperature. The warm summer of 2005 in comparison to 1982 (Figure 3) also explains the results obtained for the zoning indices that are exclusively dependent on the air temperature (Table 4), namely the indices dependent on the mean air temperature [102].

Focusing on the results obtained with the tree north of the vineyard (reference situation, without shade), $HI(2005) = 3214$ °C $> HI(1982) = 2602$ °C is explained by the higher values of the air temperature, namely the average temperature, but also the daily maximum temperature in the period April–September. Still, for the tree placed to the north, the $GSS(2005) = GSS(1982) = 180$ days. This result is justified by the climatic characteristics of the study region, in which the average air temperature tends to be higher than 10 °C in the summer, even when the weather is characterized by cloudiness and precipitation. Additionally, the model implemented in STELLA considered months of 30 days, which means that the number of days in the April–September period was 180 and not 183. In this sense, it is important to underline that some authors [103,104] consider the regions suitable for viticulture when at least 90% of days in the growing season (April–September) have an average temperature greater than or equal to 10 °C, although this ratio can be between 80% and 90% in some important wine-growing areas of North America or Western Europe.

Table 4. Results of ZM indices for the year 1982, under the influence of the trees located at a distance of approximately 3 m (T3m) and 2.5 m (T2.5m) positioned at the north, west, south, and east.

Simulation		**T3m**			**T2.5m**	
Tree location	North	West–East	South	North	West–East	South
Year			1982			
Heliothermal index, HI	2602	2462	2514	2602	2441	2467
Hydrothermal index, HyI	2379	2206	2272	2379	2179	2215
Growing season suitability, GSS	180	177	180	180	176	177
Year			2005			
Heliothermal index, HI	3214	3074	3126	3214	3053	3080
Hydrothermal index, HyI	797	725	744	797	717	720
Growing season suitability, GSS	180	180	180	180	180	180

On the contrary, $HyI(1982) = 2379$ mm °C $> HyI(2005) = 797$ mm °C; this result is a consequence of (i) HyI resulting from the product of precipitation (in mm) with the average temperature (in °C); (ii) 1982 being a year with growing season (GSP) rainfall similar to normal and much wetter than 2005; and, (iii) the difference in precipitation being much greater than the difference in temperature in these two years. The zoning indices (HI, HyI and GSS) that are dependent on the mean air temperature will also change by the influence of the tree's shade (Table 4). Higher values of these indices are obtained for higher values of average air temperature, which, in turn, depends on the insolation. Thus, higher values of HI and HyI were obtained for the tree located in the north, followed by the cases of the tree in the south and west/east. In the case of trees that cause shade, the values of these indices were higher for the tree placed at 3.0 than at 2.5 m from the grapevine because, in general, the shade increases when the distance from the tree to the vine decreases. The values of the GSS for 1982 followed these general trends, but, for 2005, were the same. This means that the shadow effect is capable of significantly altering the values of the other indices, even in the extreme conditions of 2005, but not of the GSS, especially in regions where the mean air temperature in all the days of the growing season is greater or equal to 10 °C.

It is also important to verify whether the effect of the tree's shade added to the different weather conditions of the years of study led, or not, to class changes in the values of the ZM indices. For the tree to the north (reference value, without shadow effect), the HI was much higher in 2005, indicating that this year was in the "Too Hot" class, than in 1982, indicating that this year was in the "Hot" class. Additionally, the effect of the tree's shadow led to a decrease in the HI, without leading to a class change. These results suggest that, in both years, the vine received a lot of direct solar radiation, which was beneficial for sugar production in the grapes. However, the weather conditions in 2005 favored faster grape ripening but also increased the risk of heat stress. In 1982, the HyI was relatively high, close to the limit (2500) up to which the risk of mildew contamination was low, due to the higher humidity. In 2005, this rate was significantly lower, indicating a reduced risk of downy mildew contamination due to the drier conditions. When the tree was in the west–east positions, the HyI tended to have lower values, suggesting lower water availability and the reduced risk of mildew infection, but also a greater need for careful water management. The shadow effect led to a reduction in the HyI, but not a change in the class. The GSS was consistently high (approximately 180) and did not lead to a change in the class of this index, regardless of the position of the tree to the vine and in both years, indicating the good climatic suitability of the location for vineyard growth. Despite the differences in the microclimatic conditions, the small variations between 177 and 180 suggest that the overall suitability remained high.

The shade effect helps us to understand the differences between the results obtained for the cases where the olive tree was placed east, south, and west and, therefore, how it could affect the air temperature in the grapevine [105]. The results of the zoning indices reveal the adequacy of the climate of Douro Valley for wine production, since this region has moderate water deficit stress and hot and dry summer weather, as suggested in other studies [106,107]. Even during less mild years, as in 1982, the weather was favorable to develop moderate vine vigor and exceed the heliothermal needs for the maturation of any grapevine variety and, consequently, high-quality red wine production [102]. However, during the hot years, as in 2005, the climate introduced heliothermal limitations for maturation which could limit the oenological quality [108]. The results for 2005 show higher air temperature variability (less suitability for vine), lower daily thermal amplitude in the grape maturation period, and temperate nights during the maturation period. Additionally, the values of the HyI suggested a lower risk of contamination via downy mildew in 2005 than in 1982 [109].

3.4. Plant Responses to Shading and Agroforestry Has a Climate Adaptation Strategy

Understanding the effects of shade on growth, phenology, and productivity processes is crucial when studying plant responses to varying environmental conditions, namely when dealing with agroforestry. Several studies have explored the impact of shading on different crops and species, revealing a wide range of possibilities depending on the type of plant and environmental context. For example, Cartechini and Palliotti [110] and Greer and Weedon [111] have demonstrated that shading can significantly reduce the photosynthetic activity and berry quality in specific varieties of grapevines, with variable impact on the growth and yield. Pallotti et al. [112] reviewed the effects of the shading nets as a climate change adaptation strategy and concluded that reducing photosynthetic activity can improve water use efficiency, delay the maturation process, preserve the acidity of the must, and improve the aromatic composition, but affect the phenolic compounds. Oliveira et al. [113], concluded that the partial shading of the vine canopy reduces the yield losses attributable to excessive radiation, although the musts have a lower concentration of anthocyanins and the wines have a lighter color, which can harm their quality. The varying responses to shading are also evident in the studies on shade avoidance and shade tolerance mechanisms, as highlighted by Roig-Villanova and Martínez-García [114] and Ruberti et al. [115], who discussed the adaptive strategies plants employ to cope with low-light environments. Additionally, Dillenburg et al. [116] illustrated how belowground competition from vines can affect tree growth. These studies provide a foundational understanding of plant–shade interactions, essential for developing models like IMVSCA, that aim to predict plant responses under various climatic and environmental scenarios. By integrating these diverse findings in future research, the IMVSCA model might enhance our ability to manage and optimize agricultural practices under changing environmental conditions.

In recent years, agroforestry has emerged as a critical strategy for addressing climate change adaptation and mitigation, particularly in regions vulnerable to extreme weather events and environmental degradation. Various studies have underscored the ecological, economic, and social benefits of integrating trees into agricultural landscapes, highlighting how agroforestry can enhance resilience to climate variability and contribute to sustainable development. For instance, Dhyani et al. [117] and Chavan et al. [118] demonstrate the role of agroforestry in South Asia and India in modifying microclimates, conserving biodiversity, and improving soil health. Similarly, Gebre [119] and Swamy and Tewari [120] highlighted the potential of agroforestry systems to sequester carbon and enhance soil organic matter, offering substantial climate change mitigation benefits. Lasco et al. [121] and Charles et al. [122] illustrated how agroforestry practices can improve smallholder farmers' resilience to climate-related risks by diversifying income sources and enhancing adaptive capacities in Africa and Tanzania.

These diverse benefits are closely aligned with the development objectives of the IMVSCA model, which has the long-term aim of modeling, simulating, and evaluating the impacts of various agroforestry practices on climate adaptation and mitigation. By incorporating findings from studies such as those from Raj et al. [123] and, the IMVSCA might provide a more comprehensive analysis of the effectiveness of agroforestry systems in improving farm productivity, environmental sustainability, and carbon sequestration. Furthermore, research by Rijal [124] and others highlights the importance of agroforestry as a sustainable land use practice that mitigates greenhouse gas emissions and enhances the overall resilience of farming communities to climate change. Integrating these insights in future research into the IMVSCA model will help refine its predictions and support decision-making for policymakers, researchers, and farmers aiming to improve agroforestry practices under changing climatic conditions [125].

Despite its benefits, vitiforestry adoption in Mediterranean zones faces several challenges. Key barriers include farmer conservatism, fear of failure, concerns about productivity and profitability, policies and subsidies that do not recognize agroforestry systems, and complexity in management [126]. Trees in agroforestry systems provide economic, ecological, and social benefits. However, they create a transition zone where trees and crops compete for space, nutrients, water, and light, causing stress. At the same time, trees can contribute nutrients through leaf litter and roots, potentially aiding in crop growth [127]. In addition, to be intercropped with vineyards, trees need to be compatible with modern management, including native or traditionally used trees for highly profitable market niches connected to eco-tourism [128]. Trees grown alongside grapevines influence below-ground soil conditions in vineyards, affecting water status, nutrient levels, and rooting patterns both positively and negatively [129]. Future developments of the IMVSCA model should try to incorporate the effect on the grapevine of the water status and stress management. The model might consider that trees reduce evaporation, regulate the microclimate, and distribute water through hydraulic lift, despite competition [130]. The results showed that the grapevine yield was unaffected by nutrient competition beyond 4 m from the tree rows [129]. However, at 2.5–3.23 m from the trees, high nutrient competition, especially for nitrogen, reduced the vine vigor and yield, though the berry quality remained unchanged [130]. Therefore, even if most of the studies point to the significantly enhancement of vineyard soil quality in the presence of trees, modeling the effects of nutrient levels, namely of vineyards positioned within trees (where competition is higher), would be of the utmost important. The effect of trees in increasing the rooting depth and density in grapevines by improving the soil structure and encouraging root plasticity, would be something else to be incorporated [130].

Light is a limiting resource and the amount of available light at the ground level can be modified by artificially pruning the overstory. Evolving tree structure is a manifestation of species-specific traits, site and growing conditions (e.g., competition), and the tending operations applied to the tree [131]. Tree management systems that change trunk height or remove the center pole might be important for increasing the quantity of light penetration without limiting the benefits of the agroforestry systems [132]. While effects on yield vary, reduced light lowers canopy photosynthesis, decreasing photoassimilate production [112]. However, grape quality tends to improve, associated with less sunburn, dehydration, and cell death—anyway, lower carbon assimilation slows ripening, resulting in lower sugar concentration (and less alcoholic wines), while maintaining organic acids, often lowering must pH [112]. The positive impact of trees on grape must quality, combined with the ecosystem services they provide, may offset the reduced yield in the vines located near trees. With climate change models forecasting yield and quality declines in vineyards due to rising temperatures and earlier budbreak, vineyard agroforestry systems, which help alleviate these negative effects, may prove to be more beneficial than detrimental for farmers [112].

Shade drawbacks may also include increased grapevine diseases [133]. While more research in vineyard agroforestry is needed, current studies also highlight significant pest control benefits, making diverse vineyard designs a promising approach for sustainable pest and disease management [134]. Overall, the positive below-ground benefits that trees provide, combined with ecological and cost-saving advantages, could offset any negative impacts. Although further research on tree and grapevine interactions is needed, evidence is growing that trees could play a beneficial role in the future of viticulture, namely considering climate change [129].

4. Conclusions

In this study, we intended to integrate dispersed information to evaluate the effect of shade on the grapevine's microclimate as an adaptation strategy to climate change. For this, we developed an Integrated Model of Vineyard Shading and Climate Adaptation (IMVSCA), assembled based on scattered information and innovative resources. The Light–Shadow Module includes submodules to evaluate insolation, supported by theory and robust physical and semi-empirical models, implemented mainly based on models from other authors, but also with models originally developed by us for this work. Additionally, this model also comprises phenological, zoning, and disease modules, which were based on physical, semi-empirical and empirical models or indices from previous publications. These modules aim to evaluate grapevine developmental stages, assess site suitability for viticulture, and determine the risk of disease occurrence.

The IMVSCA preliminary results were tested using meteorological data from two years with contrasting characteristics of temperature and precipitation, and similar shape and size trees, but placed at different distances and positions from the grapevine. The results obtained in this performance process are highly consistent with those expected theoretically (and from previous studies) on the effect of shade on the vineyards under divergent climatic conditions. The tree's shadow effect leads to a significant reduction in solar radiation and air temperature near the vine, especially at critical periods, with a significant impact on the phenology and in the reduction in the effects of extreme meteorological events.

We highlight that IMVSCA could include further parametrization to include processes such as temperature advection, the dynamic development of the vines and olive trees, the growth and competition of their root systems, and the intra-annual and inter-annual dynamics of water consumption and evapotranspiration, especially during climate extremes, among others. Even with all the limitations, IMVSCA already constitutes an extremely useful diagnostic tool and could support stakeholders' decisions on finding solutions to tackle the effects of climate variability and climate change on vineyards. In addition, despite the limitations inherent in a preliminary modeling demonstration, our approach can be easily applied to other case studies (regions and varieties), considering the shade from several trees with different sizes and shapes.

Finally, it is important to highlight that vitiforestry, and agroforestry systems in general, could be one of the win–win multi-functional systems able to tackle the growing demand for high-quality food production and ecosystem services conservation, and the reduction in agriculture environmental impacts, aligned with the United Nations' sustainable development goals. Favor [27] extensively, and in-depth, analyzed the interactions between olive trees and vines in vineyard agroforestry systems in an arid climate region and concluded that (i) although trees close to vineyards can reduce yield, tannins in the must due to the competition for resources and/or microclimatic effects, especially in light and water, and the shade of trees, probably influence photosynthetically active radiation and temperature, which positively influences grape characteristics, such as glucose/fructose levels and brix levels, among others; (ii) vitiforestry can help buffer the impacts of extreme weather conditions, and control pests and improve soil fertility, but its success depends on adapting to local conditions and the producer's objectives, balancing benefits and challenges; and, (iii) for wine producers, the advantages of vitiforestry can offset the yield and quality losses in conventional vineyards that are expected as a result of climate change resulting from global warming.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13111970/s1, "The detailed description of Integrated Model of Vitiforestry and Adaptation to Climate Change (IMVSCA)".

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