Future Scenarios for Olive Tree and Grapevine Potential Yields in the World Heritage Côa Region, Portugal

Helder Fraga *, Nathalie Guimarães, Teresa R. Freitas, Aureliano C. Malheiro and João A. Santos

Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), Universidade de Trás-os-Montes e Alto Douro (UTAD), 5000-801 Vila Real, Portugal; nsguimaraes@utad.pt (N.G.); trfreitas@utad.pt (T.R.F.); amalheiro@utad.pt (A.C.M.); jsantos@utad.pt (J.A.S.)

Abstract: In the World Heritage Côa region, in northern Portugal, agriculture has crucial economic, social and cultural importance. Vineyards and olive groves are part of the economic base of this region, contributing to the regional commercial budget and the livelihood of its residents. Climate change is expected to have significant impacts on these crops, where climatic conditions are already very warm and dry, posing a key threat to the olive oil and winemaking sectors. The present study analyzes the impact of climate change on the potential yield of these two crops over the Côa region. For this purpose, two crop models were initialized and run with state-of-the art spatial datasets for climate, soil, terrain, and plant data. As outputs of the crop models, potential yields of grapevines and olive trees were obtained for the recent-past (1981–2005) and for the future (2041–2070), under two climatic scenarios (RCP4.5 and RCP8.5). Results (potential yield) were then normalized, taking into account the recent-past maximum yields and divided into four classes (low, low-moderate, moderate-high, and high). For the recent-past, the results of the crop models present a high agreement with the current location of vineyards and olive groves. For the future, two different types of impacts (positive and negative) are found for the two crops. For olive trees, the results show promising future improvements in possible expansion areas within the Côa region. However, for grapevines, the results show a decrease in potential yields throughout the region, including a strong shift of producing moderate zones to low potentials. Nonetheless, these results also suggest that the negative impacts of climate change can be alleviated by the application of suitable adaptation measures, based on changing certain management practices, even in the more severe future scenario. Therefore, these measures should be carefully planned and implemented in a timely fashion by farmers.

Keywords: climate change; olive groves; vineyards; crop modelling; STICS; warming; drying; viticulture

1. Introduction

In inner-northern Portugal, the Côa region has strong ties to the agrarian sector, with century-old traditions. In this region, agriculture has crucial economic, social and cultural importance, contributing to the regional commercial budget and the livelihood of its residents. In fact, agriculture is the economic base of this region, which is considered a World Heritage Site by UNESCO since 1998. In the Côa region, vineyards and olive trees account for more than 10% of the total land-use area (Figure 1b). The wine and olive oil markets represent a strong source of income for most of the inhabitants of these areas. Furthermore, part of the Côa region is located within the Douro Demarcated Region (more specifically the Douro Superior sub-region), a renowned PDO (protected denomination of origin) and recognized wine brand worldwide. Other crops, such as almond trees, chestnut trees, and grassland are also part of the agronomic livelihood of this region, although to a smaller extent.

It is known that olive trees and grapevines are highly influenced by climatic factors, which largely impact the agricultural suitability of a particular region. Given the climatic specificities of the Côa region, with warm and dry summers, and wet and moderately cold...
winters, these typical Mediterranean crops (grapevines and olive trees) are particularly suited for these areas. Nonetheless, climate change is expected to have significant impacts on the atmospheric conditions in this region, with a particular effect on agriculture and grown crops [1–5]. Over the last century temperatures have significantly increased all over the globe [6], whereas precipitation and water availability have significantly decreased over southern Europe [6]. Additionally, future projections for these Mediterranean-type climatic regions are in line with these trends, since significant warming and drying are projected for the coming decades [6]. As the current Mediterranean warm-dry summers are already limiting for certain crops, mainly due to scarce water resources in summer. Grapevines and olive trees are considered to be drought-tolerant crops, with a minimum requirement of annual precipitation of around 350 mm [7,8]. However, climate change may threaten these crops, which may become particularly vulnerable to a changing climate, without adaptation measures. Climate change, although it may represent an important threat, may also be seen as an opportunity to develop suitable and cost-effective adaptation measures and risk management policies [9–12]. Their implementation can significantly mitigate the impacts of climate change on these crops and on the regional/national economy in general.

Figure 1. (a) Digital elevation model (DEM) of Portugal. The boundaries of the Côa region are highlighted in red. (b) Olive orchard and Vineyard land cover distribution across the Côa region following the COS2018. (c) The regional municipalities and main rivers within the Côa region.

Crop models are steadily becoming standard instruments to support agronomic decision-making [13–16]. State-of-the-art, mechanistic/dynamic crop models essentially try to simulate plant growth and development by integrating weather data, plant and soil characteristics, and management practices [17–20]. Despite being applied to a large array of crops worldwide (e.g., wheat, maize, rice), crop models are still not widely used for grapevine or olive trees, when compared to annual crops (e.g., maize), perhaps given the perennial nature of these crops [21–26]. Nonetheless, in the past decades, some efforts have been developed along this line of research and these models are more actively being developed and used within the olive/grapevine research communities [27–36]. Given their large complexity, crops models are continuously updated with new scientific knowledge and are becoming more and more reliable and robust.
The use of high spatial resolution datasets is of significant importance for crop model usage, as it is necessary to properly capture environmental variability within and between regions, particularly in terms of environmental and agricultural changes [37]. This is particularly relevant for regions with steep climatic gradients, e.g., mountainous regions, where low-resolution datasets may not represent the crop micro-climatic conditions. In the Côa region, vineyards and olive groves are usually laid out on the valleys and are very dependent on the elevation, slope, and aspect, which represent the complexity of the Côa topography (Figure 1a). Local meteorological effects are important factors controlling both the development and spatial distribution of these crops. The diverse local microclimatic conditions must be taken into account to produce reliable crop model outputs. Typically, Global Climate Models (GCM) offer data with spatial resolutions of about 100–250 km, while Regional Climate Models (RCM) offers data with relatively higher spatial resolutions of about 10–25 km [38–41] (see Figure 2 for an example of the resolution). Although these datasets are extremely useful their typical resolutions cannot capture the spatial heterogeneity of a small region, such as Côa. Therefore, the use of high-resolution downscaled data (1 km or less) has proven to be an important advance for regional/local scale assessments and a better integration with crop models [42–44] (see Figure 2 for an example of the resolution).

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Figure 2. Schematic representation of the methodologies used in the present study.

2. Materials and Methods
A schematic representation of the methodology is shown in Figure 2.
In the present study, an assessment of the climate change impacts on the potential yield of olive trees and grapevine is performed over the Côa region. For this purpose, two different dynamic crop models are used with state-of-the-art spatial datasets for climate, soil, terrain, and plants. Two different future scenarios, a more moderate and a more severe scenario, are used. The differences between recent-past and future potential yields are discussed, as well as possible adaptation measures to counteract the negative impacts of climate change.

2. Materials and Methods

A schematic representation of the methodology is shown in Figure 2.

2.1. Study Area

The Côa region is located in northern Portugal close to the border with Spain (Figure 1a). It includes several municipalities and encompasses completely the Côa river basin, and partially the Douro and Mondego rivers (Figure 1c). In order to assess the distribution of olive orchards and vineyards in the Côa region, the land cover dataset COS2018 was used. Regarding the olive orchards and vineyards growing areas (Figure 1b), the region has approximately $28 \times 10^3$ ha and $25 \times 10^3$ ha, respectively [45]. Regarding the spatial distribution, it is clear that these two crops occupy very similar niches, although the vineyard area is more concentrated in the northern part of the region, being also areas within the Douro Superior winemaking region PDO. In the central part of the region, which is an area of higher elevations, only vineyards are found, whereas olive groves are found in areas in the southernmost part of the Côa region. The Côa region presents a typical Mediterranean-like climate with an annual temperature between $13–15 \degree C$ and precipitations between 450–700 mm (Figure 3).

Figure 3. (a) Annual mean temperature ($\degree C$) and (b) annual precipitation sum (mm) over the Côa region for present conditions (1981–2005) from the E-OBS dataset.
2.2. Crop Models

Two different crop models were used in the present study, which have already been used in several other studies for climate change impact assessment [4,32,46]. These models are run on a daily time-step simulating crop growth development from the start until the end of the growing season and they require a large number of parameters describing local conditions, such as soil profile characteristics (e.g., soil depth, texture, porosity); technical parameters (e.g., leaf area index, start and end of the growing season) and daily weather variables (e.g., precipitation, maximum and minimum temperature).

For the olive tree modelling, the dynamic olive tree model developed by Viola, Noto, Cannarozzo, La Loggia and Porporato [32] was used (henceforth olive dynamic model). This is a water-driven crop model [32], previously used in site-specific assessments of yield variables and climate change assessments [20]. As this model requires some specific inputs (particularly growing season start-end), another model was coupled, which was developed by Orlandi, et al. [47]. This model provides the annual start and end of the vegetative cycle based on a bioclimatic “growing season index” of olive trees.

Grapevine modelling was based on the crop model STICS [48]. This well-established model was developed by the French National Research Institute for Agriculture and Environment (INRAE) and has been successfully applied to simulate a wide variety of crops [34], including grapevines [49–51]. Moreover, this crop model has also been previously used for climate change impact assessment on several crops [52–54].

2.3. Climate Data

The required daily weather variables by the crop models include maximum air temperature (Tmax; °C), minimum air temperature (Tmin; °C), solar radiation (Rad; W m⁻²), total precipitation (Prec; mm), wind speed (Wspeed; m s⁻²), relative humidity (Rh; %) and CO₂ levels (ppm). All of these variables were obtained from EURO-CORDEX datasets [40] for the recent-past period (1981–2005) and the future period (2041–2070) under two distinct scenarios, i.e., a more moderate (RCP4.5) and more severe climate scenarios (RCP8.5). For this purpose, data from four global-regional climate model chains (GCM-RCM, Table 1) were retrieved from the EURO-CORDEX project [40] at a ~12.5 km spatial resolution. These two different scenarios and four GCM-RCM model chains are important to access the scenario and model uncertainty associated with climatic modelling. In RCP4.5, CO₂ emissions are assumed to increase until the mid-21st century, decreasing afterward, whereas the CO₂ emissions continue to rise until the end of the 21st century in RCP8.5 [6]. These CO₂ emission differences between scenarios are particularly relevant in terms of the increase in global temperature, resulting in a higher increase in temperature in RCP8.5, compared to RCP4.5. Given that the 12.5 km spatial resolution is not enough to capture the climatic heterogeneity within a small region, such as the Côa, these data was downscaled to 1 km spatial resolution using a multivariate linear regression methodology, with latitude, longitude and elevation as independent variables. This approach is similar to well-known databases, such as WorldClim [55]. Subsequently, bias correction methodologies were applied using the “Empirical Quantile Mapping” methodology [56] to correct possible bias in the downscaling approach.

Table 1. List of the ensemble members used in this study, along with their respective institutions.

| GCM-RCM                      | Institutions                                  |
|------------------------------|------------------------------------------------|
| CNRM-CERFACS-SMHI-RCA4       | Centre National de Recherches Météorologiques |
| IPSL-CM5A-MR-SMHI-RCA4       | Institut Pierre Simon Laplace                  |
| MOHC-HadGEM2-SMHI-RCA4       | Met Office Hadley Centre                       |
| MPI-M-MPI-SMHI-RCA4          | Max Planck Institute                           |
2.4. Other Datasets

Soil data required by the crop models were obtained from the Harmonized World Soil Database HWSD [57]. Soil properties from the HWSD are available from two layers (depths 0–0.3 m and 0.3–1.0 m). Additional soil properties were estimated using pedotransfer functions (Bouma, 1989). Topographic/terrain data were obtained from the Portuguese DGT “Direção Geral do Território” digital elevation model at 10 m resolution (accessed on 15 December 2021: https://www.dgtterritorio.gov.pt/cartografia/cartografia-topografica/modelos-digitais-do-terreno). Regarding the management practices, it was necessary to apply a large-scale comprehensive modelling approach throughout the Côa region. Hence, some assumptions were made concerning grown varieties and cultural practices. All parameters used for crop modelling are described in Table 2.

Table 2. Parameters required by the crop models (olive tree and grapevine), along with the corresponding datasets used for their calculation and key references.

| Parameter                                      | Calculation                       |
|------------------------------------------------|-----------------------------------|
| Clay content in the surface layer (%)          | HWSD                              |
| Limestone content in the surface (%)           | HWSD                              |
| Soil pH                                         | HWSD                              |
| Albedo of the dry soil                         | [58]                              |
| Cumulative evaporation limit (mm)              | [59]                              |
| Fraction of runoff in soil                     | [60]                              |
| Dominant soil unit (FAO)                       | HWSD                              |
| Permeability classes                           | [61,62]                           |
| Texture class                                   | HWSD                              |
| USDA Texture                                    | HWSD                              |
| Mean slope (%)                                  | GTOPO30                           |
| Orientation                                     | GTOPO30                           |
| Initial soil water content set at field capacity|                                   |
| Soil organic N                                 | 6% dry soil                       |
| Maximum unimpeded root depth                   | 2.0 m                             |
| Olive canopy cover fraction                    | 0.4                               |
| Olive tree LAI                                 | 1.4 m²·m⁻²                        |
| Vine density                                    | 4000 vines/ha                     |
| Vine trellis system                             | Bilateral Cordon                  |

2.5. Model Runs

The crop model uses the described input daily variables and provide annual estimates of potential yields. For each period (recent-past and future), the annual potential yields were averaged. The outputs were then separated into classes according to the following methodology. Firstly, the obtained potential yields, for the recent-past and future periods, were normalized regarding the maximum potential yields in the recent-past. This normalization process allows comparing the potential yields in percentages between 0–100%. Secondly, the potential yield was divided into four classes: 0–25%—low yield, 25–50%—low-moderate yield; 50–75% moderate-high yields; and 75–100% high yields.

3. Results

3.1. Results for Olive Trees

Regarding the recent-past potential olive yields in Figure 4, it is evident that the olive dynamic model shows a very good agreement with the olive orchard distribution within the Côa region. This is a clear indication that the model is suitable for modelling the olive potential yields, and is also in agreement with previous studies [4,48]. Table 3 provides a summary of the yield classes in terms of areas (ha). In the recent-past, the model projects that the high potential yield areas are very limited spatially (1% of the full area of the Côa). In effect, our results indicate that almost all of the region is divided into two yield classes. The northernmost and southernmost areas of the Côa region present moderately-high
potential yields (42% of the all area), while the central part of the region presents low potential yields (57% of the all area). As was already mentioned, presently, in these low potential yield areas, although quite extensive, almost no olive orchards are found. These areas are also high altitude areas, which may indeed present challenging conditions for olive trees, due to night-time low temperatures (frost damage). Furthermore, some of these areas also show other challenging conditions for cultivation, such as poor soils and low water availability.

Figure 4. Olive tree potential yield classes (quartiles) over the Côa region for the present (left panel), RCP4.5 (upper right panel) and RCP8.5 (lower right panel) for 2041–2070. The potential yield classes correspond to the ratio between the actual value at each grid box and the absolute maximum for the entire target region in the present conditions period. The olive tree orchard areas are also highlighted (green-shaded).

Table 3. Summary of the potential yield classes by area (in hectares), for the present, RCP4.5 and RCP8.5. Values inside parentheses represent the percentage of the total area of the region.

| Yield Class | Present | RCP4.5 | RCP8.5 |
|-------------|---------|--------|--------|
| Olive tree  |         |        |        |
| Low         | 327,121 (57%) | 0 (0%) | 0 (0%) |
| Low-Moderate| 0 (0%)  | 39,651 (7%) | 272,797 (48%) |
| Moderate-High| 237,254 (42%) | 528,181 (93%) | 295,035 (52%) |
| High        | 3456 (1%) | 0 (0%) | 0 (0%) |
| Grapevine   |         |        |        |
| Low         | 188,930 (33%) | 226,363 (40%) | 279,775 (49%) |
| Low-Moderate| 18,717 (3%) | 100,236 (18%) | 30,390 (5%) |
| Moderate-High| 173,408 (31%) | 241,232 (42%) | 257,667 (45%) |
| High        | 186,777 (33%) | 0 (0%) | 0 (0%) |

Under future climates, the patterns of potential yields in the Côa change drastically. For both scenarios, the crop models show an increase of potential yields in the high altitude areas of central Côa. In fact, low yield areas in the future may be reduced to 0 ha, significantly improving the regional overall growth conditions. This could indeed be an effect of higher temperatures in the future climate, improving the conditions for olive tree dissemination. Conversely, despite this improvement of the growing conditions for areas where there is presently low suitability for olive groves, for the rest of the olive-growing
Table 3. Summary of the potential yield classes by area (in hectares), for the present, RCP45 and RCP85. Values inside parentheses represent the percentage of the total area of the region.

| Yield Class      | Present          | RCP45           | RCP85           |
|------------------|------------------|-----------------|-----------------|
| Olive tree       |                  |                 |                 |
| Low              | 327,121 (57%)    | 0 (0%)          | 0 (0%)          |
| Low-Moderate     | 0 (0%)           | 39,651 (7%)     | 272,797 (48%)   |
| Moderate-High    | 237,254 (42%)    | 528,181 (93%)   | 295,035 (52%)   |
| High             | 3456 (1%)        | 0 (0%)          | 0 (0%)          |
| Grapevine        |                  |                 |                 |
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3.2. Results for Grapevines

Regarding the results of the grapevines crop model STICS, there is also a clear agreement between the modelled potential yields and the current grapevine land cover distribution (Figure 5). See Table 3 for a summary of the yield classes in terms of areas (ha). The highest potential yield are found in the northern Côa region, in the Douro Superior wine-producing sub-region, as well as in the southernmost part of the Côa region, which is not currently populated by vineyards. The two areas account for 33% of the total area of Côa, located in the high-yield class. Nonetheless, the fact that the southern part of the region is not populated by grapevines could be a result of a modelling limitation within the STICS model. Despite this drawback, it is clearly shown that the Côa currently shows moderately-high (31%) to high potential yields (33%) in the present vineyards.

For the future, the crop model shows a different outcome for grapevines than for olive trees. As a matter of fact, vineyard productivity is expected to decrease for all of the Côa vineyard areas, changing from 188,930 ha (33%) in the present to 226,363 ha (40%) in RCP4.5 and to 279,775 ha (49%) in RCP8.5. Furthermore, in some westerly areas, the decrease is particularly harsh, changing directly from moderately-high yields to low yields. Thus, it becomes clear that all areas are predicted to decrease in terms of potential yields, especially since in both scenarios high yield areas are not found (0 ha).
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Figure 5. Same as Figure 4 but for the grapevine potential yields.

4. Discussion

The present study is focused on the application of two crop models to olive trees and grapevines to assess present (1981–2005) and future (2041–2070) mean potential yield, across the World Heritage region of Côa in northern Portugal. For this purpose, the two crop models were coupled with state-of-the-art climate, soil, and terrain datasets. The modelling outputs for the recent-past properly identify the main producing areas in terms of potential yields and show an overall agreement between these areas and the current land cover for both olive trees and grapevines. The areas corresponding to low potential yields currently cover a large spatial extent within the Côa region (57% for olive trees and 33% for grapevines). For grapevines and olive trees, both models show generally favorable conditions under the present climates, particularly in the northern and southern parts of the region. Conversely, in the central Côa, conditions for these crops are currently challenged. Given the coherence between the modelling outputs and the current distribution of these two plants it becomes clear that the combination of crop models could indeed be beneficial for site-specific modelling of different crops.
Applied to climate change scenarios, the crop model projections indicate different impacts of climate change for these two crops. Currently established viticulture in the Côa will undergo many changes until the mid-21st century, due to the decrease in potential yields projected for the region. Low yield areas may increase in acreage from 188,930 ha in the present, to 226,363 ha in RCP4.5 and 279,775 ha in RCP8.5. Although a catastrophic scenario is not predicted to occur, some areas may still experience large decreases in yield, such as the Douro Superior wine producing region, although the projected potential yields will still be within the moderately-high class, in both future scenarios.

For olive trees, the future impacts seem to be less negative. A large portion of the central area of the Côa region, which until the present showed very low suitability for olive production, most likely due to low temperatures at higher elevations, will tend to improve its climatic conditions for olive tree growth. Changes will lead to a disappearing of the low-yield areas (0 ha). Indeed, temperatures below −5 °C tend to damage olive branches and significantly limit development [20]. Higher future temperatures will tend to be generally favorable, making these regions more suited for olive trees. These results confirm that olive tree is particularly adapted to hot and dry conditions, having developed key survival strategies. The small leaf size, high leaf reflectance and adapted positions to sunlight promote decreased radiation interception and sensible heat diffusion [63]. Olive tissues can also withstand very negative values of xylem water potential (e.g., stem water potential <8.0 MPa; [64]). Further, hydraulic redistribution in olive roots (allowing superficial roots to remain active during summertime) was observed recently in southern Portugal [65]. Other olive tree strategies to improve drought adaptability were also reported previously [63].

It must be pointed out, however, that both crops, olive trees and grapevines (e.g., [66] reviewed grapevine drought responses), are considered climate-resilient. Therefore, they are a valuable asset to reduce land degradation and desertification within the Côa region. To achieve this goal, attention should be given to the promotion and adoption of adaptation measures in these two important sectors. One of the main adaptation measures to future warmers and drier climates is the improvement of crop water use efficiency [67,68]. Soil tillage, mulching, or cover cropping may also potentially increase water use efficiency and soil moisture [69,70]. Regarding cover crops, special attention should be given to the selection of a proper seed mix, not competing with the main crop for soil water during the driest season. Water scarcity and competition will be one of the main problems in some areas in the future, and smart irrigation and smart-farming policies should also be privileged in this region that already deals with excessive water stress [71]. In the past, in the Douro PDO, irrigation was highly restricted, due to policy rules. Nonetheless, over the last years, the increase in water and heat stress has been leading to a shift in these policies, and irrigation is becoming more accepted and adopted.

To adapt to climate change, the growers/farmers have a critical decision-making role. Particularly in the Côa region, where small estates are predominant, the role of the grower is considered crucial. For example, when a new orchard or vineyard is being planned, it is important to take into account climate change studies for the next decades. Presently, in the Côa region, Touriga-Franca, Touriga-Nacional and Aragonez are the most the grapevine varieties, while the olive varieties of Galega, Cornicabra, Carrasquenha, Negrinha, Madural e Cobrançosa are the most planted ones. These grapevine and olive varieties have already proven to have a high resilience to adverse climatic conditions in the present, but may be challenged under future scenarios. Therefore, special attention should be given to a proper selection of the most suitable variety/clone/rootstock, bearing in mind not only the present climate but also on future projections. Drought and heat resistant plant material should be carefully selected, to be best suited for the climatic characteristics of the region [72,73].

Regarding the new potential areas for olive tree cultivation, this can be seen as a long-term measure, since the displacement of olive cultivation to higher elevations [21] to escape severe heat and water stress is indeed projected. Nonetheless, given that the structure of the Côa region is composed by small farms, this would be very difficult to implement. Regarding these new areas for cultivation, some issues should be taken into consideration,
such as water availability, proper soil characteristics, and suitable terrain conditions for planting and management. Given the results shown in the current study, it is clear that adequate and timely planning of suitable adaptation measures needs to be adopted by the olive oil and wine sectors. The adoption of these measures should be, however, explored in each olive orchard and vineyard, taking into account the specificities of each site. In effect, the ability to adapt to climate change will be the major determinant factor for assessing the magnitude of the projected impacts [22]. A gradual adaptation to a changing climate may indeed reduce the detrimental impacts and risks. Additionally, thinking ahead for the next 30–40 years may provide competitive advantages for the sectors.

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