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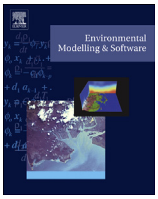

Modelling olive trees and grapevines in a changing climate[☆]

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ABSTRACT

The models developed for simulating olive tree and grapevine yields were reviewed by focussing on the major limitations of these models for their application in a changing climate. Empirical models, which exploit the statistical relationship between climate and yield, and process based models, where crop behaviour is defined by a range of relationships describing the main plant processes, were considered. The results highlighted that the application of empirical models to future climatic conditions (i.e. future climate scenarios) is unreliable since important statistical approaches and predictors are still lacking. While process-based models have the potential for application in climate-change impact assessments, our analysis demonstrated how the simulation of many processes affected by warmer and CO_2-enriched conditions may give rise to important biases. Conversely, some crop model improvements could be applied at this stage since specific sub-models accounting for the effect of elevated temperatures and CO_2 concentration were already developed.

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1. Introduction

Grapevine and olive tree represent worldwide key economic activities with Europe representing the largest vineyard area in the world (38%, Fraga et al., 2012) and olive tree widespread cultivated around the Mediterranean basin (Vossen, 2007). Besides their economic importance, the cultivation of these species provides a number of services for the society, including landscape maintenance and improvement, enhancement of the quality of life, and ecological and environmental services (Loumou and Giourga, 2003; Nieto et al., 2010).

Centuries of experience in the cultivation of these crops have resulted in a strong association of both olive and grapevine growing with geographically distinct regions in European countries (Jones et al., 2005; Moriondo et al., 2013a,b). Over these areas, olive trees and grapevines are confined to specific climatic niches that put them at greater risk from temperature and rainfall changes. For instance, rising temperatures, as predicted in future climate scenarios, might alter the phenological responses of olive trees (i.e. timing of flowering, end of dormancy as well as minimum chilling requirements) (Avolio et al., 2012), as well as a gradual northward shift of current olive cultivation areas in the coming decades (Moriondo et al., 2013b; Tanasijevic et al., 2014). Extreme events (both in temperature and precipitation), as expected in future climate scenarios, could have a strong impact on grape growth and wine quality (Jones et al., 2005), especially if they occur during the growing season (Jones and Davis, 2000).

Olive grove and grapevine productivity, and consequently profitability, depend on several factors including soil fertility, management practices, climate and meteorology. Since the profitability of a crop is a prerequisite for its cultivation, there is a subsequent need for a reliable assessment of the effects of a changing climate on its yield and quality. This would help to define the possible economic impact on the areas where they are currently cultivated, as well as on the regions in which cultivation could become viable in the future.

In this context, crop models are essential tools for investigating the effects of climate change on crop development and growth via the integration of existing knowledge of crop physiology relating to changing environmental conditions. This approach could provide a unique opportunity to assess possible effects of a warmer climate on crop yield and quality, as well as to evaluate different adaptation options for reducing or exploiting the effects of a changing climate. As such, crop models were extensively applied to assess the potential of various crops on farm, regional and national scales. In

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particular, during the last 20 years, these tools were applied at different time and spatial scales to assess the potential impact of climate change on crop productivity, thereby providing a reliable benchmark to establish relevant adaptation options (White et al., 2011).

Despite their widespread use in studying crop productivity for both the present and future scenarios, crop models have shown limitations, which may simply be represented by the fact that when applied in similar conditions, different models often provide different results (Palosuo et al., 2011; Rötter et al., 2012; Asseng et al., 2013). These differences are usually related to the specific approach used to describe a certain process that may be either over-simplified or even incorrectly outlined (Eitzinger et al., 2013).

Based on these premises, this paper provide a review of different models, either generically adapted to, or specifically developed for simulating grapevine and olive tree growth and development by focussing on the major limitations of these models, especially in their application to climate change impact and adaptation assessments.

The analysis first considers the type of modelling approach, i.e. empirical or process-based by detailing the level of their parameterization. Differences in the approaches adopted for the simulation of the main processes such as phenology, leaf-area growth, photosynthesis, biomass accumulation and partitioning, and water and nutrient stress were further analysed for the process-based model. The strengths and weaknesses of each simulated process were evaluated and discussed in view of the recent advances in crop modelling. The analysis specifically outlined the following: i) the processes that are not yet simulated but may play an important role in climate-change impact assessment (e.g. the effect of increased CO_2 on radiation and water-use efficiency, RUE, WUE) (Tubiello and Ewert, 2002); ii) the effects of extreme events on crop yield (Moriondo et al., 2011a); iii) the impact on yield quality.

2. Modelling approaches

The models selected for this analysis can be divided into two categories, namely (i) empirical and (ii) process-based. In the first category, statistical methods are used to generally describe a linear relationship between the dependent (e.g. crop yield) and predictor variables accounting for the fact that climate (e.g. climate indices such as cumulated rainfall or average temperature of a certain month) is one of the key factors influencing yield quantity and quality (Jones et al., 2005). Conversely, other processes like plant development, Leaf Area Index (LAI) growth, and nitrogen dynamics in the soil are not considered. These models may be summarized according to the following linear equation:

$$Y_j = \alpha T_{ji} + \beta R_{ji} + \cdots + \delta$$

where Y is the yield quantity or quality, T and R are predicting variables aggregated at different time scales (i) (usually monthly, seasonal or yearly) in the year (j), α, β are the regression coefficients, and δ is the intercept.

As such, empirical models need a limited amount of input data to produce an output but causes-effects mechanisms between climate and yield are not explicitly described and this limits the applicability of this approach to the specific regions or environmental conditions for which the relationships were calibrated.

Conversely, in process based models, crop behaviour is defined by a range of relationships describing the main plant processes. Crop models working at different levels of detail basically include the simulation of 1) *crop development*, which indicates the period by which crop growth should get started, the priorities in dry matter partitioning, and the maturity; 2) *biomass accumulation*, which is a function of the amount of Photosynthetically Active Radiation (PAR) intercepted by the canopy and the efficiency via which the intercepted PAR is converted into dry matter. Depending on the model, potential biomass accumulation may then be reduced by water, nitrogen stress, or heat stress; 3) *biomass partitioning* to the different organs, (leaves, stem, fruit, and roots) according to the priorities during the plant life cycle, providing a feedback for updating the simulation of leaf area extension and the growth of stem, fruit and roots (Fig. 1).

A specific sub-class of these models include functional models that are oriented to simulate specific plant processes such as daily CO_2 exchange or water dynamics in the soil while sketching or neglecting other processes such as phenology, biomass partitioning or abiotic stresses.

Further, process-based models, originally designed to work on field scale (Sinclair and Seligman, 1996), explicitly includes non-climatic factors, such as management practices (e.g. sowing dates, fertilization) or soils type, as determinants of crop yield.

As such, process based models, may be easily applied to simulate crop yield on a local scale, provided that climatic and non-climatic information are available at the required scale.

Based on these premises, the different approaches used to simulate plant growth and development were compared separately for each category of model, emphasizing the relevant limitations in the light of new findings in the specific approach.

2.1. Empirical models

The driving variables used to fit empirical models for yield prediction are generally temperature (T) and rainfall (R) aggregated on a monthly timescale (Table 1). Despite the large variability of the environments where these models were parameterized, there is a generally good agreement regarding the variables selected as the best predictors of final yield. This implies that these models are able to detect the importance of critical stages in determining final yield, even when there is a rough resolution of the input variables.

Under this context, Nemani et al. (2001) correlated the positive trend in grapevine yield of the Napa valley (1963–1996) to the

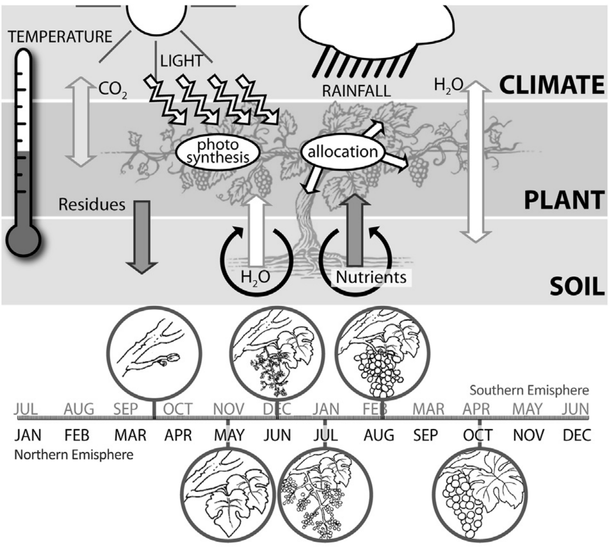

Fig. 1. Outline of a possible structure of a process-based model. Leaf intercepted radiation is converted into biomass that is allocated to different plant organs (leaves, stems, trunk and roots) according to the phenological stage. Abiotic stresses (nitrogen and water suboptimal conditions) affect this scheme e.g. by reducing photosynthetic efficiency and the pattern of biomass allocation.

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