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Ecological Modelling

Modelling the dynamics of grapevine growth over years

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ABSTRACT

A process-based model was developed to simulate the dynamics of grapevine growth within and over years. The model was designed so that it could be used in a later stage to incorporate damage mechanisms of grape diseases, and to analyse their effects on growth and yield over consecutive seasons. The development stage is modelled according to temperature. The within season-dynamics includes (1) the production of assimilates from photosynthesis, (2) the reallocation of assimilates from roots and trunk during the vegetative phase of the crop cycle, (3) the partitioning of assimilates towards leaves, stems, grapes, roots, and trunk, (4) the accumulation of assimilates in roots and trunk after maturity, and (5) leaf senescence. Winter and within-season pruning are also included. The model was parameterised for *Vitis labrusca* using literature and experimental data. The model was tested with data collected from a 5-year-old vineyard of *V. labrusca* cv. Niagara Rosada, and evaluated by comparing outputs with data from the literature. The model satisfactorily reproduced the general dynamics of plant growth within year and over successive seasons. Simulation over 20 years indicated that biomass of leaf, stem, grape, and trunk at grapevine maturity increased according to a sigmoid dynamics, while a near-linear increase in roots dry biomass was simulated.

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1. Introduction

Crop growth simulation models developed over the last decades have allowed major advances in better understanding the processes at play, in integrating in a formal and quantitative way the knowledge acquired, in identifying knowledge gaps, in guiding research and inform policies, and in improving crop management decisions (Jones et al., 2017; Savary et al., 2006). The bulk of these efforts have been invested on annual crops (Jones et al., 2017; Penning de Vries et al., 1989), whereas perennial crops or tree species have been considered in a more limited way (Burkhart and Tomé, 2012; Goldschmidt and Lakso, 2005; Landsberg, 1986; Le Roux et al., 2001). The main additional processes to consider in the case of perennial crops, as compared to annual crops, are polyetic processes, that is, processes involved over years or over crop cycles (Zadoks and Schein, 1979). Such processes involve the storage of reserves, and the consecutive use of these reserves, which depend on the balance between source and demand (Kozlowski, 1992).

In the case of grapevine, several crop growth models have been developed, with varying broad objectives, e.g., better understanding of processes and knowledge synthesis (Bindi et al., 1997a; Gutierrez et al., 1985; Nendel and Kersebaum, 2004), optimization of pruning according to yield and quality (Lakso and Poni, 2005), improvement of water management (Valdés-Gómez et al., 2009), or decision making for crop management (Cola et al., 2014). The dynamics over successive years was simulated by the model developed by Nendel and Kersebaum (2004), but the dynamics of reserves was not explicitly simulated by the model. Conversely, the model developed by Gutierrez et al. (1985) and expanded to account for nitrogen dynamics (Wermelinger et al., 1991) explicitly simulates the reserves dynamics, but does not simulate crop growth over years.

Crop growth models that incorporate damage mechanisms associated to injuries from pests (diseases, insects, and weeds) have been developed in order to analyse the effects of pests on the physiological processes of crop growth and yield build-up. Seven damage mechanisms have been identified (including, e.g., light stealing, photosynthesis reduction, and senescence acceleration) which capture the range of mechanisms through which physiological processes are impaired by pests (Boote et al., 1983; Rabbinge and Rijsdijk, 1981; Rabbinge and Vereyken, 1980). The damage mechanisms are generic, because they can be applied to the range of pests which are damaging crops, and because they operate in the same way for perennial and annual crops (Savary and Willocquet, 2014).

In the case of perennial crops, the effects of injuries from pests may further translate into polyetic processes: because they affect crop physiology, damage mechanisms may affect the reserves dynamics, therefore impacting crop growth processes occurring during the next crop cycle. This impact is designated as secondary loss (Zadoks and Schein, 1979), i.e., loss impacting the crop in later years. Secondary losses have been documented for a few pests affecting perennials, e.g., in the case of coffee diseases (Cerda et al., 2017). A disease such as grapevine rust rarely causes primary loss (loss occurring during the crop cycle), because infection mainly occurs after harvest (Primiano et al., 2017). It may be hypothesized that the disease causes secondary losses because reserve accumulation after crop maturity may be affected by the disease, leading to a reduced growth at the beginning of the next year, when reserves are used to start the growth (Nogueira Júnior et al., 2017).

Several models including damage mechanisms have been developed on annual crops such as wheat (Rossing, 1991; Willocquet et al., 2008), rice (Pinnschmidt et al., 1995; Willocquet et al., 2004), and potato (Johnson, 1992; van Oijen, 1992). Very few models have been developed in order to analyze the effects of diseases or pests in the case of perennial crops (Rodríguez et al., 2013). To our knowledge, no crop growth model for grapevine that includes damage mechanisms for diseases or pests has been developed yet.

The objective of this work was to develop a simple, generic, and parameter-sparse crop growth model for grapevine which incorporates key physiological processes that occur during a crop cycle and between successive crop cycles and that can be potentially affected by grapevine pests and diseases. Here, we test the performance of the model in reproducing the growth and development of healthy grapevine plants as a precondition for future simulations of pest and disease effects on grapevine. The model is applied to the American grapevine, *Vitis labrusca*. The model was designed in order to be as robust as possible, and so that it could be used in the future to analyze the effects of diseases on the physiology and yield of grapevine over successive growing seasons.

2. Material and methods

2.1. General approach

The model described here is designed to incorporate in a later stage damage mechanisms caused by diseases and address primary and secondary losses. The objective of the model implies three important specifications: (1) the model needs to include processes which are affected by diseases through damage mechanisms; (2) the model needs to incorporate polyetic processes in order to simulate crop growth over years; and (3) the model needs to simulate in a satisfactory way the growth in the absence of diseases or insect pests, that is, the attainable growth. An additional criterion (4) is that the model is to be as simple as possible, i.e., to include processes according to the specific objective of the model.

In order to fulfill the first criterion, the model was designed so as to include all processes affected by diseases. The damage mechanisms described by Boote et al. (1983), Rabbinge and Rijsdijk (1981), and Rabbinge and Vereyken (1980) represent the starting conceptual and methodological stepping stones for the model development. The model GENECROP (Savary and Willocquet, 2014) was recently developed as a generic crop growth model which allows considering damage mechanisms for annual crops, and was used as a baseline model for the present analysis. The second criterion was fulfilled by incorporating in the model processes which are important for between-season dynamics, i.e., the dynamics of reserves in the trunk and in roots.

In order to fulfill the third and fourth criteria, the following approach was used, which is derived from Willocquet et al. (2008, 2004, 2002, 2000). Yield loss is the difference between the attainable yield and the actual yield. The attainable yield is influenced by determining factors such as radiation and temperature (which determine the potential yield), and by limiting factors such as water and nutrients (Rabbinge et al., 1989; van Ittersum and Rabbinge, 1997; Zadoks and Schein, 1979). The attainable yield is in turn a reflection of the production situation where a crop is grown, i.e., the socio-economic and bio-physical environment where agricultural production takes place (Rabbinge et al., 1989; Savary et al., 2017). Since the ultimate objective of the model is not to analyze the effects of limiting factors on crop growth, processes such as water and nutrient cycles in the soil were not considered explicitly. Instead, the processes involved in the attainable growth and yield are reflected according to production situation drivers, i.e., drivers that determine the attainable growth. These drivers include drivers which determine the potential growth (van Ittersum and Rabbinge, 1997; Zadoks and Schein, 1979) such as temperature and radiation, as well as drivers which reflect the effects of limiting factors on growth. Water and nutrients represent the main limiting factors. They affect mainly the efficiency of photosynthesis and the acceleration of leaf senescence (Munne-Bosch and Alegre, 2004; Sinclair and Horie, 1989). Parameters of the model that represent photosynthesis efficiency and leaf senescence were used as proxies to reflect the effects of limiting factors on growth. This allowed accounting for the effects of limiting factors on the attainable growth in a simple way.

2.2. Overall structure of the Genecrop-P model and associated hypotheses

We developed Genecrop-P as a simple agrophysiological model for a perennial crop. The structure of Genecrop-P is derived from Genecrop (Savary and Willocquet, 2014; Fig. 1A), which is a simple, generic crop growth simulation model for annual crops. The system modelled in Genecrop-P is one plant, and the model time step is 1 day. As in Genecrop, Genecrop-P simulates within-season crop development (crop phenology) and crop biomass dynamics, whereby the increase in organ biomass originates from a pool of assimilates, which is produced from photosynthesis. Genecrop-P further considers between-season dynamics, and an additional process leading to the increase in assimilated biomass: the reallocation of assimilates from roots and trunk reserves (Fig. 1B). The model simulates the plant-scale dynamics of the development stage (DVS), the dry biomass of different organs, the leaf area (LA), as well as the leaf area index (LAI). The overall structure of the simulation model Genecrop-P developed for grapevine is displayed in Fig. 1C. The model considers five plant organs (fruits, stems, roots, trunk, and leaves), the flow of carbohydrates to these different organs, as well as the reallocation of assimilates from roots and trunk. The model state variables, rates, driving functions and parameters are listed in Table 1.

The development stage of grapevine is scaled from 0 to 4 as follows (Lorenz et al., 1995): bud break (DVS = 0); flowering (DVS = 1); maturity (DVS = 2); leaf fall (DVS = 3); and dormancy (DVS = 4). Bud break begins after the dormancy period. This stage corresponds to the beginning of the active growth phase of the grapevine plant. The operational definition of bud break is when 50% of green shoots tips are clearly visible. Flowering starts after the end of the vegetative period, i.e., 40–60 days after bud break, depending on the temperature. The flowering development stage is operationally defined as the stage when more than 50% of inflorescences have at least 10% of the flower hoods dropped (Lorenz et al., 1995). Maturity occurs when berries begin to brighten in colour. The operational definition for maturity is when 100% of berries are ripe for harvest. Leaf senescence begins after harvest, and ends when all leaves have fallen. The operational definition of leaf fall is when 100% of leaves