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Research article

Analyzing the impacts of climate change on ecosystem services provided by apple orchards in Southeast France using a process-based model

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ABSTRACT

We know that fruit production, especially in the Mediterranean, will need to adapt to climate change to ensure the sustainability of fruit tree-based agroecosystems. However, there is a lack of evidence on the long-term effects of this change on sustainability indicators. To fill this gap, we used a fruit tree model, QualiTree, to analyze the impacts ofclimate change on the ecosystem services provided by apple orchards in south-eastern France. To do this, a blooming model was parameterized to simulate blooming date on the basis of climate data, and QualiTree was supplemented with a model of nitrogen processes in the tree and a soil module describing resource input (irrigation, mineral and organic fertilization), transfer in the soil (water and nitrogen) and metabolic transformation-immobilization (mineralization, (de)nitrification). This type of extension makes it possible to simulate a wide array of ecosystem services, including C sequestration, nitrate leaching and nitrous oxide emissions. The model was compared with data from an apple orchard in southeastern France. The predicted daily mean and variability over time of fruit growth, composition and soil water content were consistent with observed data. QualiTree was then used to assess the potential impacts of climate change on the ecosystem services supplied by apple orchards. For this purpose, weather variables from 2020 to 2100 were generated for three contrasted greenhouse gas emission scenarios, and simulations were performed under two irrigation schemes (no restriction and restricted use of water). Model outputs indicated that, on average, marketable apple yields would increase until 2050 and then subsequently decrease. The fruit refractometric index, an indicator of fruit quality, was projected to sharply decrease with the intensity of climate change. Ecosystem services such as C sequestration by the orchard will decrease with climate change severity, mainly due to a higher mineralization of soil humus, whereas N_2O emissions will increase with larger denitrification rates. Soil water availability, fertility, drainage and leaching were predicted to depend more on the irrigation strategy than on climate change severity. The new functions performed in QualiTree broadened its predictive capabilities and allowed for a better understanding of ecosystem service delivery in fruit orchards under varying climate conditions.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2021) has projected increases in temperature of 2.5–5.5 °C by 2100. Climate and environmental changes are putting pressure on water use for irrigation (Fereres and Soriano, 2007), and their impacts on agriculture will be more severe over the coming years especially in the Mediterranean area (Masia et al., 2021). In addition, mean annual precipitation is predicted

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to decrease by 10–30% in many parts of Southern Europe (European Environment Agency, 2021), especially in the summer, and precipitation patterns will change, with more frequent heavy rainfall and drought events (IPCC, 2021). These changes will have a significant effect on fruit orchards, due to their perennial character, impacting on crop yields and most likely on fruit quality and non-marketed ecosystem services.

Therefore, fruit orchards are facing multiple challenges at this time. On the one hand, the quality of harvested fruits must be maintained or even improved to encourage their consumption (Codron et al., 2005), while maintaining high yields, because farmers' incomes depend mainly on the quantities produced. This has led to horticulture intensification through large use of inputs. On the other hand, there is an urgent need to reduce the negative impacts of these practices on natural resources and ecosystem functioning (Pulido-Bosch et al., 2018; Cui et al., 2023), since fruit orchards deliver a wide range of ecosystem services beyond fruit production (Demestihas et al., 2017). The conceptual framework of ecosystem services could help to address this duality (Power, 2010; Reid et al., 2005). The perennial character of trees, the multi-strata habitat and the plant diversity within the boundaries of orchards may contribute to maintaining or promoting a high degree of biodiversity, the driver of ecosystem services (Simon et al., 2010), while orchards also have a great potential to sequester carbon (Zanotelli et al., 2015). These specificities, among others, make fruit orchards interesting for ecosystem service analysis (Demestihas et al., 2017; Mudare et al., 2023). However, orchard ecosystem functions interact dynamically and vary according to environmental conditions, especially climate change, and to cultural practices, including irrigation and fertilization. These interactions could lead to both positive and negative relationships between ecosystem services, whose quantification is a challenge (Demestihas et al., 2017).

Process-based models have emerged as useful tools for enhancing our comprehension of the complex and interlinked processes that control tree growth, fruit size and composition at different organizational levels (Martre et al., 2011; Grisafi et al., 2022). Moreover, these models may help us to study how crops and the provision of ecosystem services within agroecosystems react to environmental and management changes (Vos et al., 2007; Demestihas et al., 2018). In the case of fruit trees, models are available for several species (for a comprehensive review, see Grisafi et al., 2022), including apple (Costes et al., 2008; Lordan et al., 2019), almond (Esparza et al., 1999), kiwi (Cieslak et al., 2011), grapevine (Mirás-Avalos et al., 2018), olive (López-Bernal et al., 2018), and peach (Allen et al., 2005; Lescourret et al., 2011). However, only a few models account for the effects of both water and carbon availability and allocation within the tree on fruit production under stressful environments, mainly because functions such as water and nutrient uptake are often disregarded (Grisafi et al., 2022). An exception is L-PEACH where the growth of individual organs is affected by stem water potential and not just by carbon partitioning (Da Silva et al., 2011). Furthermore, these models do not consider ecosystem services provided by fruit tree orchards, except for yield.

The QualiTree model (Lescourret et al., 2011) combines ecophysiological and agronomic viewpoints for describing carbon and water acquisition and allocation within the tree, vegetative and fruit growth distributions, and the development of fruit quality. Previous versions of QualiTree have been successfully calibrated and validated with experimental data (Mirás-Avalos et al., 2011, 2013; Rahmati et al., 2018). However, due to the absence of a soil compartment, QualiTree was not able to simulate soil functioning and could therefore not account for some of the ecosystem services that fruit tree orchards are able to provide (Demestihas et al., 2017). Several recent studies addressed the challenge of simulating ecosystem services in fruit tree orchards (Demestihas et al., 2018, 2019). However, these studies made use of generic models that did not account for the specificities of tree crops, such as plant architecture and carbon allocation within the trees.

Apple (*Malus domestica* Borkh.) is a major fruit crop in the world, with 96 million ton of apples produced worldwide in 2022 (FAOSTAT, 2024). Moreover, this species is grown in a wide range of environments, from cold to Mediterranean climates (Cornille et al., 2019). In addition, several ecosystem services in apple orchards have been determined in previous studies (Demestihas et al., 2018). Therefore, this species is a good model for assessing the impacts of global change on different ecosystem services in fruit tree orchards. In this context, the aims of this study were to (i) improve the virtual fruit-tree model, QualiTree, by implementing a blooming model and a soil module, as well as the modeling of the tree nitrogen processes; (ii) include the calculation of many ecosystem services related to production, climate regulation, water cycle and soil nitrogen availability; and (iii) assess, through model simulations, potential impacts that climate change may have on the delivery of ecosystem services in apple orchards.

2. Materials and methods

2.1. The original QualiTree model: a virtual fruit tree

QualiTree is a generic fruit tree model that describes the tree as a set of objects. Some of them are viewed globally, including old wood (trunk and branches), water sprouts and roots (coarse and fine), whereas the fruiting units (FU) consist of fruits, leafy shoots and stem wood (Lescourret et al., 2011). The FU are connected to old wood within an explicit architecture (geometry and topology). The interception of solar radiation is calculated over the growing season to simulate both photosynthesis (Mirás-Avalos et al., 2011) and radiation balance (Rahmati et al., 2018) at each FU.

Photosynthesis was simulated using the Farquhar's model because it describes the biological functioning of photosynthetic mechanisms in response to CO_2 concentration, which will increase with climate change. Moreover, QualiTree computes energy balance (Sinoquet et al., 2001), stomatal conductance (Jarvis, 1976) and water flow within the tree's three-dimensional architecture (Vercambre et al., 2002). Leaf water potential is an output, allowing QualiTree to represent the effects of water deficit on photosynthesis and vegetative and fruit growth, as described by Rahmati et al. (2018).

QualiTree formalizes the growth in dry mass of the tree organs following a carbon supply approach, allocation rules and growth requirements (demands). The main equations are described in Lescourret et al. (1998, 2011). Moreover, QualiTree simulates the development of fruit quality traits such as size, flesh dry matter content and concentrations of various sugars (Génard et al., 2003). QualiTree considers the effects of environmental conditions and agricultural management on tree growth and fruit quality traits (Mirás-Avalos et al., 2011, 2013). From an initial state of the tree, QualiTree runs on a daily time-step (hourly for water balance and photosynthesis), as of or after bloom until the end of the growing season. Parameters and validations for apple can be found in Juillion (2022).

2.2. Addition of a soil module to QualiTree

The soil module in QualiTree is based on the STICS model (Beaudoin et al., 2023), which describes the soil as a sequence of horizontal layers, each characterized by its water content and mineral and organic nitrogen and carbon contents, as well as by other properties such as texture and bulk density. Soil and crop interact through the roots, which are defined in terms of root density distribution within the soil profile.

Soil hydraulic properties (water content at field capacity and wilting point, bulk density) are assumed to be constant in each horizon (Beaudoin et al., 2023).

The evaporation of water from the soil is computed in two stages according to Ritchie (1972). In the first stage, the actual soil evaporation is set equal to the potential evaporation. This stage is only limited by the supply of energy to the soil surface and continues until the accumulated potential evaporation reaches a given threshold. In the second stage, water movement to near-surface evaporative sites is controlled by soil hydraulic properties, resulting in actual evaporation being reduced with respect to potential evaporation. Simulated soil water content links the soil module to the virtual tree.

Root uptake is computed over the root profile and is then distributed to soil layers, as reported by Cook and Dent (1990), according to the distribution of roots in the soil profile.

Nitrogen mineralization originates from the humified organic matter and the crop residues. The humified organic matter is mineralized up to a depth at least equal to the plowing depth. The nitrification rate is calculated as the product of a potential rate and control factors: availability of substrate (NH_4) and environmental conditions (pH, soil water content and temperature). Similarly, denitrification is calculated using nitrate (NO_3^-) as a substrate. The N_2O emissions associated with the two former processes are also described (Léonard, 2016).

Inputs of nitrogen in its mineral form include synthetic nitrogen fertilizers (urea, ammonium, nitrate) and nitrogen from precipitation and irrigation (Beaudoin et al., 2023). The transfer of nitrate nitrogen in the soil is simulated by a functional, reservoir-type model where the soil horizons are divided into elementary 1-cm layers. The water draining from a given layer to that immediately below carries a certain amount of nitrate, which is assumed to mix completely with the water (Millington and Quirk, 1961). The process then continues down to the bottom of the profile or to a layer in which the water content remains lower than the field capacity (Beaudoin et al., 2023).

2.3. *Modeling of tree nitrogen processes in QualiTree*

QualiTree considers that each tree organ consists of three compartments: (1) a structural dry mass, including C and N compounds; (2) a reserve of C; and (3) a reserve of N. The nitrogen used by the tree affects compartments (1) and (3), and, consequently, compartment (2).

The algorithm describing the nitrogen processes in the tree comprises five operations, which take place at a daily time step: (i) the uptake of N from the soil by the new roots; (ii) the calculation of the N demand of the different tree organs; (iii) the provision of N to organs; (iv) the impact of N availability on organ growth; and (v) the update of nitrogen reserves.

Nitrogen uptake U(l) (gN day^{-1}) by the fine roots in each soil layer (l) is described by a Michaelis-Menten equation, similar to that proposed by Habib et al. (1989) for peach trees:

$$U(l) = \frac{V_m N_s(l)}{(K_m + N_s(l))\left(1 + \frac{N_p}{K_n}\right)} \times WS_{nr} \times r_p(l) \tag{1}$$

where WS_{nr} is the dry mass of fine roots of the tree (g DM), $r_p(l)$ is the proportion of fine roots in the layer, V_m is the maximal absorption per unit of dry mass, $N_s(l)$ is the concentration in soluble N of the soil layer (gN L^{-1}), K_m is the Michaelis affinity constant (gN L^{-1}), and K_n is an inhibition constant (gN gDM^{-1}) leading to negative feedback of N_p, the nitrogen reserve of the fine roots (gN gDM^{-1}) on nitrogen uptake.

The nitrogen absorbed and coming from easily mobilizable reserves is distributed to the organs for their growth so that the organ growing patterns direct the nitrogen fluxes, as previously reported (Munoz et al., 1993; Policarpo et al., 2002). The nitrogen demand for each organ is calculated according to the C growth demand and a fixed organ's N concentration in the structural dry mass (Bossel, 1996; Bossel et al., 1991). The N obtained by an organ is in proportion to its demand. For each organ, if the N obtained is lower than the demand, the growth demand is reduced to maintain the fixed level of N concentration in the structural dry mass. Reserves of N, essential for the functioning of fruit trees (Carranca et al., 2018), are replenished from the available N after growth in proportion to the structural dry mass. However, the model assumes that, except for old roots and wood, there is a maximum of N reserve content in the total dry mass of a given organ that cannot be exceeded. At each time step, a maximum reserve of N is calculated, and when this threshold is surpassed, the excess amount is allocated to old roots and wood in proportion to their structural dry masses, as they can store C and N resources, such as starch and vegetative storage protein (Gomez et al., 2020).

2.4. *Blooming model in relation to climate change*

A sequential model, incorporating a chilling sub-model (triangular) and a heating sub-model (sigmoid), was developed to forecast dormancy release and blooming of apple trees (Legave et al., 2013). The model was fitted using the Phenology Model Platform (PMP5.5, Chuine et al., 2013), with data collected from phenological observations on the "Golden delicious" cultivar over 27 and 31 years at two locations in southeastern France, along with climate data from local weather stations.

2.5. *Ecosystem service indicators and analysis*

QualiTree outputs correspond to nine indicators selected and adapted from Demestihas et al. (2018) and Lacroix et al. (2024) that describe four ecosystem services at the scale of the growing season (year), namely fruit production, soil nitrogen availability, climate regulation and water cycle maintenance and regulation (Table 1). Fruit production is defined by the marketable yield (Ymarket), which is the mass of those fruits that surpass a given threshold weight, and by the refractometric index of marketable fruits (BRIX), an indicator of fruit quality. Soil nitrogen availability is defined by the mean nitrate concentration in the 0–30 cm soil layer (mNO3) and the variation in organic nitrogen (varN). Climate regulation is described by carbon sequestration (Cfix) and by the total N_2O emissions (tN2O), which contribute positively and negatively, respectively. Carbon sequestration, here limited to what is associated with the apple trees, is calculated as the sum of the carbon fixed in the soil (i.e., the variation of active carbon in the humus pool of the soil) and the tree (i.e., variation in dry mass of all tree organs, with the exception of harvested fruits). Total N_2O emissions are the sum of the N_2O emitted from nitrification and denitrification processes (either from the N contained in the fertilizers or the soil organic matter). Water cycle maintenance and regulation are described by the temporal dynamics, over the season, of the daily mean water content in the 0–30 cm soil layer (mWC), the water drainage, computed as the excess supply of water in the last layer of the simulated soil (drain), and nitrate leaching (tNleach), which depends on drainage.

Table 1

Ecosystem service indicators, abbreviated names, and units used in the current study, adapted from Demestihas et al. (2018) and Lacroix et al. (2024).

Service	Indicator	Abbreviated name	Unit
Fruit production	Marketable yield	Ymarket	$\text{t ha}^{-1}\ \text{year}^{-1}$
	Refractometric index of marketable fruits	BRIX	°BRIX
Soil nitrogen availability	Variation of organic nitrogen	varN	$\text{kg N-humus ha}^{-1}\ \text{year}^{-1}$
	Mean nitrate concentration in the 0–30 cm soil layer	mNO_3	$\text{mg N-NO}_3^-\ \text{kg}^{-1}$ of dry soil
Climate regulation	Total N_2O emissions	tN2O	$\text{kg N-N}_2\text{O ha}^{-1}\ \text{year}^{-1}$
	Carbon sequestration (carbon fixed in soil and trees)	Cfix	$\text{t C ha}^{-1}\ \text{year}^{-1}$
Water cycle maintenance and regulation	Mean water content in the 0–30 cm soil layer	mWC	$\text{g water cm soil}^{-3}$
	Water drainage	drain	mm year^{-1}
	Nitrate leaching	tNleach	$\text{kg N-NO}_3^-\ \text{ha}^{-1}\ \text{year}^{-1}$

2.6. Experimental data to test the model

To test this upgraded version of QualiTree, we used data from a study carried out in 2019 at the experimental station of La Pugère, located in southeastern France (Mallemort, France: 43.74°N; 5.125°E), with a typical Mediterranean climate (mean temperature and precipitation during the season were 20.3 °C and 250 mm, respectively). The orchard (0.22 ha) consisted of 10-year-old 'Golden Delicious' apple trees (*Malus domestica* Borkh.) grafted on 'Pajam® 2 Cepiland', with a centrifugal training system. This cultivar is the most widely grown in France, accounting for almost 25% of production. Trees were spaced 1.25 m within rows and 4 m between rows (2000 trees/ha). The orientation of the rows was north to south (16° east). Trees were managed following the Integrated Fruit Production practices for fertilization, pest and weed control (IOBC, 2018). A white anti-hail net that reduced the incident radiation by 9% was installed above the entire orchard from May to October. The soil at this site was clay loam (20% clay), 1-m deep, from the Durance River's limestone and alluvium deposits. The field capacity was 25% of the soil dry mass and the wilting point was 12%, with a water holding capacity of 169 mm. The soil at La Pugère had 41% of the volume of limestone, pH was 8.5, and mean organic carbon and nitrogen contents (0–30 cm) were 12.8 and 1.4 g kg^{-1} of dry soil, respectively. Analytical determinations of soil organic carbon and nitrogen were performed following ISO standards (ISO14235 for C and NF ISO13878 for N). The total carbon concentration was measured by dry combustion with an elemental analyzer.

A micro-sprinkler irrigation system with one emitter per two trees with a flow rate of 35 L/h made it possible to avoid water deficits since irrigation was managed to maintain midday stem water potential values above −1.5 MPa (Naor et al., 1995). The micro-sprinkler watered the row and partially the inter-row, which was covered with grass, while the row was kept bare by means of mechanical weeding. In the inter-row the grass was mowed and shredded during the season. Pruning material was also shredded and left on the soil surface. Their incorporations into the soil were progressive and this was considered in the model through the organic matter content of the upper soil layer, measured at the beginning of spring.

Temperature and relative humidity were recorded using HygroVUE10™ sensors (Campbell Scientific) located in the canopy every 30s and averaged every 5 min. Radiation sensor (SP1110 skye, Campbell scientific) were located close to orchard, as well as the rain gauge (AGR100, Campbell scientific). Soil water content was measured using TDR probes (CS650) along six soil profiles placed under the rows of trees and distributed throughout the orchard. The probes were inserted at depths of 10, 40 and 70 cm and connected to a data logger (Campbell scientific). Measurements were taken every 20 min.

In the orchard, 10 trees were selected, and 2 fruits per tree were destructively sampled every 2 weeks for measurements (fresh and dry mass, refractometric index, fruit composition), leading to less than 7% of fruit removal according to the initial crop load. Fruit dry mass was measured after drying to a constant weight at 65 °C in an oven. The refractometric index (°Brix) was determined for each fruit (ATAGO™ PR-32α Digital brix refractometer). The soluble sugars and starch were measured using a microplate reader, an efficient tool for separate enzymatic analyses of sugars in plant tissues (Gomez et al., 2007). Other fruit compounds are calculated as the fruit dry mass substracted by the starch and soluble sugars quantity. A relationship was estimated to predict the refractometric index from the soluble sugar concentration of the fruit, a Qualitree output. During the winter, the length of all shoots was measured on three trees, enabling us to estimate the tree's total leaf area on the basis of an allometric relationship.

2.7. Input data and model parameters

Climate data (including temperature, relative humidity, rainfall, global solar radiation and wind speed) collected at a weather station located in the experimental orchard were used as model inputs. Tree architecture was defined from experimental measurements of diameters and lengths of tree axes, and insertion and phyllotaxic angles. The soil analyses carried out during the late winter (March 12) prior to the experiment provided the initial mineral, organic nitrogen and carbon contents (Table 2). Initial values for leafy shoot and fruit dry masses were taken from the experimental data at the beginning of the season.

Relevant input values related to the soil module and the nitrogen processes in the tree are presented (Supplementary Material Table 1). Most of the parameters specific to the soil module were collected from Beaudoin et al. (2023) and Léonard (2016), and are listed in the Supplementary Material Table 1.

2.8. Climate change projections and simulation scenarios

To test the effects of climate change on the ecosystem services provided by the apple orchard, a set of climate scenarios was defined. Climate projections were generated with the CNRM-CM5 model (Voldoire et al., 2013). CNRM-CM5.1 includes the atmospheric model ARPEGE-Climat (v5.2), the ocean model NEMO (v3.2), the land surface scheme ISBA and the sea ice model GELATO (v5) coupled through the OASIS (v3) system. Bias correction and statistical down-scaling method were then applied with a spatial resolution of 8 × 8 km^2 within the framework of the DRIAS project (Lémond et al., 2011). The Avignon (Latitude: 43°56′54″ N, Longitude: 4°48′32″E, Elevation above sea level: 31 m) region was then selected and projections of CO_2 concentration, daily minimal, maximal and mean temperatures, wind speed and rainfall were simulated for three Representative Concentration Pathways (RCP) of interest, namely RCP 2.6, RCP 4.5, and RCP 8.5 (IPCC, 2021), for the period 2020–2100. The RCPs refer to different emission scenarios, providing an estimated increase of global mean surface temperatures at the end of the 21st century that probably ranges between 0.3 and 1.7 °C for RCP2.6, between 1.1 and 2.6 °C for RCP 4.5, and between 2.6 and 4.8 °C for RCP 8.5. The reference period extends from 1951 to 2005.

Two irrigation strategies were applied for all climate scenarios. The first strategy replicates current farmer practices, namely water is supplied to fulfill the crop's needs (ETc), computed daily based on the reference evapotranspiration for a given year and climate scenario (ETo), and multiplied by the crop coefficient (Kc). The evolution of Kc over the season is based on the estimates of Zanotelli et al. (2019) for an apple orchard. This situation therefore corresponds to an optimal irrigation with no water stress. For the second strategy, it is assumed that the water available for irrigation will be the same as that in 2019, even if the climatic demand and crop water needs were higher, leading to deficit irrigation. A reduction factor was applied to Kc throughout the

Table 2
Input values of the soil module in QualiTree and obtained from field measurements at the experimental orchard. When several values appear separated by a hyphen, each one refers to a soil layer.

Parameter	Definition	Unit	Value
mew_0	Initial soil water content	mm water cm^{-1} soil	3.1–3.5 – 3.9–3.9
$nOrg_0$	Initial soil organic nitrogen concentration as a function of each horizon	g N-humus kg $soil^{-1}$	0.69–0.5 – 0.0057–0.0075
$csAMM_0$	Initial ammonium concentration as a function of each horizon	g N-NH_4^+ kg $soil^{-1}$	0.008–0.008 – 0.002–0.002
$csNit_0$	Initial nitrate concentration as a function of each horizon	g N-NO_3^- kg $soil^{-1}$	0.00619–0.00626 – 0.00663–0.00658
$cOrg_0$	Initial soil organic carbon content as a function of each horizon	g C-humus kg $soil^{-1}$	6.9–5.0 – 0.064–0.070
pH	Soil pH at a given layer	–	8.6–8.7 – 8.0–8.0
mef_c	Water content at field capacity (mesopore)	mm water cm^{-1} soil	3.9–3.95 – 4.25–4.05

season so that the seasonal cumulative amount of water used for irrigation was equal to the amount used in 2019. In this case, we considered that even if the climatic demand increases, water resources may be limited at the territorial level, and irrigation may then become limited in relation to the orchard's needs.

We carried out simulations with the QualiTree model, which combined the two irrigation strategies mentioned above and climate change scenarios for each year during the reference period (1951–2005) and the projections (2000–2100) to evaluate their impacts on ecosystem services. In total, 716 scenarios were simulated (55 years for the reference period, 101 years for each of the three RCP scenarios, all crossed with two irrigation strategies).

The yearly values of QualiTree outputs were subjected to time series analysis to assess their trend by calculating their means. The autocorrelation function was used to examine how a value depended on the preceding values over a period of time. The Ljung-Box test was used to assess whether autocorrelation within a given output was different from zero (Ljung and Box, 1978). It tests the overall randomness based on a number of lags (in this work, 15). Time-series analyses were carried out in the R statistical environment, v.4.1.1 (R Core Team, 2021).

3. Results

3.1. Model fitting: soil water content, vegetative and fruit growth, refractometric index

This upgraded version of QualiTree satisfactorily estimated the volumetric water content of soil at three depths (10, 40 and 70 cm) over the growing season (Fig. 1). The model correctly reacted to both rainfall and irrigation events, despite an overestimation of soil water content at a depth of 10 cm by mid-July (days after full bloom 80, Fig. 1). Tree water status dynamics over the season, both in terms of predawn and minimum water potential, were also well reproduced by the model although simulated values were slightly underestimated (Supplementary Material Fig. 1).

QualiTree correctly simulated the evolution of fruit fresh and dry mass over the course of the growing season, but it slightly overestimated their values during mid-growth (Fig. 2). The magnitude of these

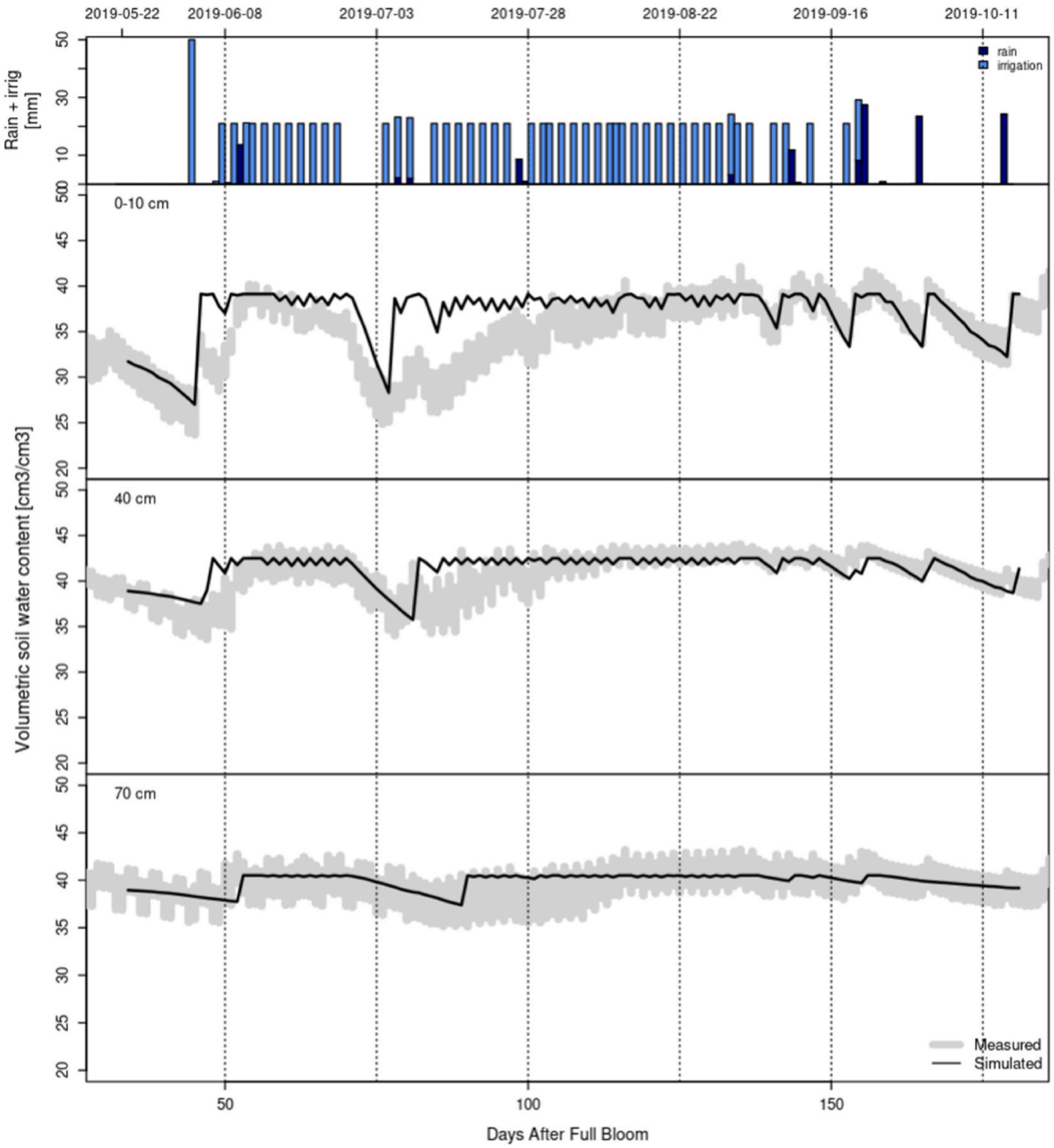

Fig. 1. Test of the model vs. experimental data. Dynamics of soil water content at three depths (10, 40 and 70 cm) over the course of the growing season in an apple orchard located in Southeast France. Gray bars are the range of the measured values (n = 6) and black lines are the simulated ones. Rainfall and irrigation events over the season are also displayed.

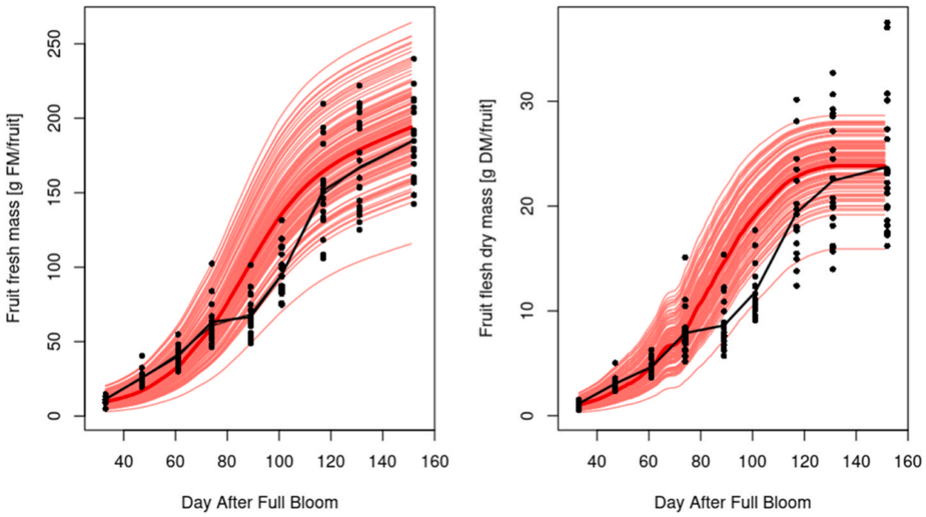

Fig. 2. Test of the model vs. experimental data for apple trees grown in Southeast France. Variation of fruit growth in fresh and dry mass among monitored shoots vs. days after full bloom, either observed (n = 20 for each date, black circles for the individual fruit or lines for the mean value) or simulated (thin red line for the individual fruit and thick for the mean value).

deviations was quantified by means of the root mean squared error, which was 26.3 g and 3.8 g for the fresh and dry mass, respectively. Moreover, the model was able to account for the large within-tree variability in both fresh and dry mass (Fig. 2). Concerning fruit composition, the simulated patterns of the concentration of soluble sugars in the fruit flesh correctly fitted the experimental values (Fig. 3), as well as those for starch and other compounds with root mean squared error values of 0.86, 0.5 and 1.24 g/100 g FM respectively for the soluble sugars, starch and other compounds. Vegetative growth was correctly simulated, both for its dynamic and maximal growth since the simulated maximal leaf surface of the tree was 13.85 m^2, whereas the measured surface was around 14.3 ± 0.1 m^2 (n = 3).

3.2. Climate change impacts on weather variables and plant phenology

The mean temperature during the growing season increased from 2005 to 2100 across all climate change scenarios. However, the magnitude of this increase varied between scenarios, with the mean temperature reaching 22.07 °C in 2070–2100 for the RCP 2.6 scenario, but almost 24.66 °C for the RCP 8.5 scenario, compared to a reference mean temperature of around 20.35 °C. Similarly, the cumulative potential evapotranspiration amounted to around 865 mm for the reference scenario, 1000 mm in 2070–2100 for the RCP 2.6 scenario, but was 1092 mm for the RCP 8.5 scenario (Fig. 4). Rainfall amounts decreased with the severity of climate change (by 9% compared to the reference period at the end of the century and for the worst scenario) and were not autocorrelated among years, probably due to a high interannual variability. Cumulative irrigation amounts for fulfilling tree water requirements increased up to 23.6% with the severity of climate change compared to the reference period. This was accompanied by a large increase in atmospheric CO_2 concentration, which was 400 ppm in 2100 for the RCP 2.6 scenario, and reached 900 ppm in the RCP 8.5 scenario (Fig. 4).

Despite these variations in temperature, blooming occurred around mid-April regardless of the scenario, probably due to the opposing effects of the large shift at the end of chilling with global warming and a similar reduction in the duration to accumulate heat requirements.

In QualiTree, harvesting is triggered when the starch content of the fruit falls below a predetermined threshold. The harvest date remained stable regardless of climatic changes and irrigation strategies. Thus, neither climate change nor irrigation scenarios affected the time at which the starch content of the fruit fell below this threshold. No

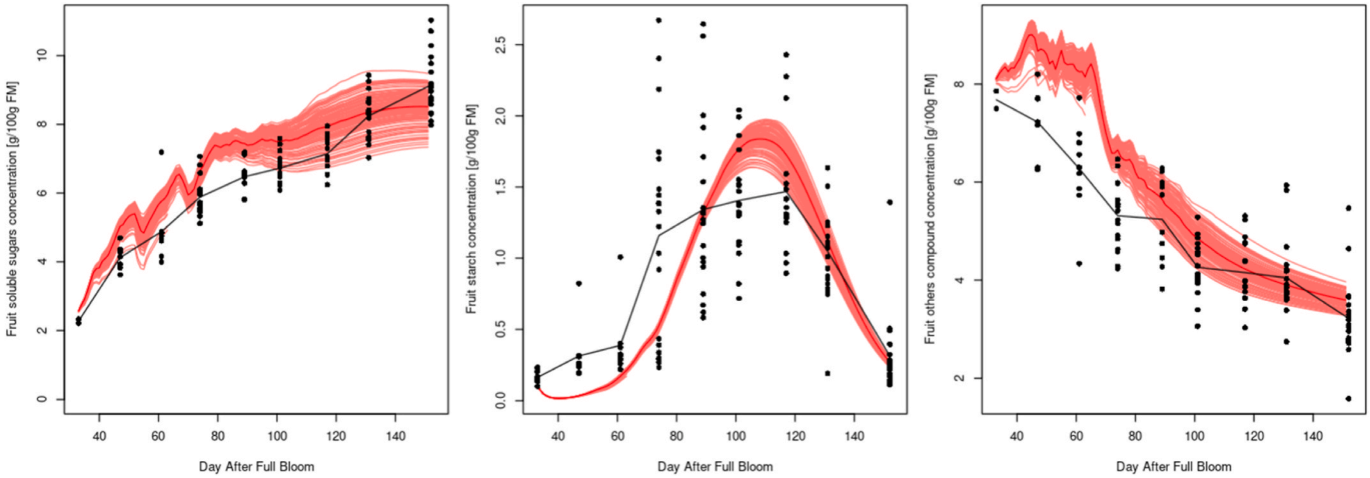

Fig. 3. Test of the model against experimental data for apple trees grown in Southeast France. Variation of fruit concentrations in soluble sugars, starch and other compounds vs. days after full bloom (observed: n = 20 for each date, black circles for the individual fruit or lines for the mean value; simulated: thin red line for the individual fruit and thick for the mean value).

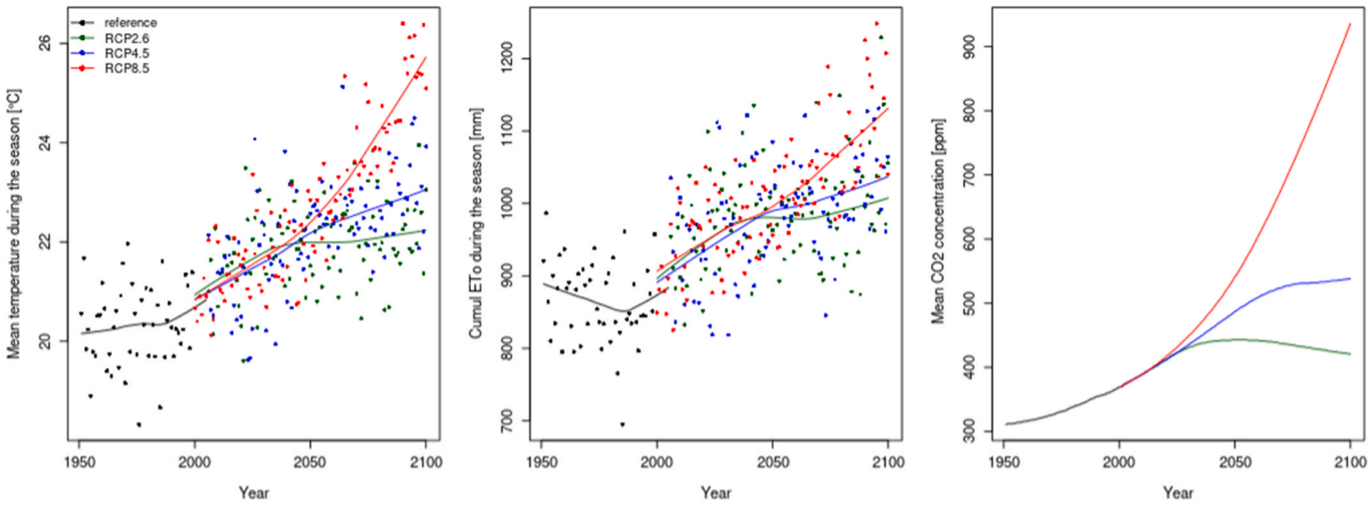

Fig. 4. Evolution of mean temperature, cumulative reference evapotranspiration (ETo) over the growing season and air CO_2 concentration for the reference period (1950–2005) and the three climate change scenarios (RCP 2.6, 4.5 and 8.5) during the period 2005 to 2100, in the Avignon region (Southeast France). Points are individual years and lines reflect the general trend for each scenario.

autocorrelation among years was found in this data series.

3.3. *Climate change effects on ecosystem services supplied by apple tree orchards*

3.3.1. *Fruit production*

QualiTree simulations showed that marketable apple yield tended to increase (6–8% on average) until 2040–2050, increasing from an overall mean value of 77.9 t ha^{-1} in the reference scenario under optimal irrigation, to 84.3 t ha^{-1} in the RCP 4.5 scenario with optimal irrigation (Fig. 5; Supplementary Material Table 2), despite the severity of the climate change scenario. Behind these average values for the different scenarios, the trends show a decrease after 2050 of around 80 t ha^{-1}, except for the RCP 4.5 scenario in which it remained stable at approximately 85 t ha^{-1} (Fig. 5). Overall, the variability of marketable yields ranged from 50.4 to 96.8 t ha^{-1} year^{-1} (Table 3). Similarly, fruit fresh mass increased until 2050 (reaching 205 g per fruit on average), but decreased below 195 g per fruit in 2100 for the RCP 8.5 scenario (Fig. 5). As expected, irrigation restrictions had a decreasing effect on both marketable yields and fruit fresh mass, but this effect was low in comparison to that caused by the climate change scenarios (Fig. 5; Supplementary Material Table 2).

In the case of the refractometric index of marketable fruits, the simulations predicted a sharp decline from values around 10.5°Brix in 2005 to less than 8°Brix in 2100 for the RCP 8.5 scenario, and around 9.5°Brix for the other two climate change scenarios (Fig. 5). Limiting irrigation amounts slightly counteracted this decline in the refractometric index for a given scenario (Fig. 5; Supplementary Material Table 2). Half of the series showed autocorrelation.

The rise in temperature associated with global change had a very strong effect on the duration of fruit growth and, consequently, on the accumulation of dry mass in the fruit (Supplementary Material Fig. 2). For the most adverse scenario, this meant a shortening duration of up to 20 days. The increase in photosynthesis with the increase in atmospheric CO_2 concentration (Supplementary Material Fig. 3) partially offset this reduction in growth time.

3.3.2. *Soil nitrogen availability*

Regarding the service of soil nitrogen availability, the variation in organic nitrogen was almost always negative (Table 3), indicating that

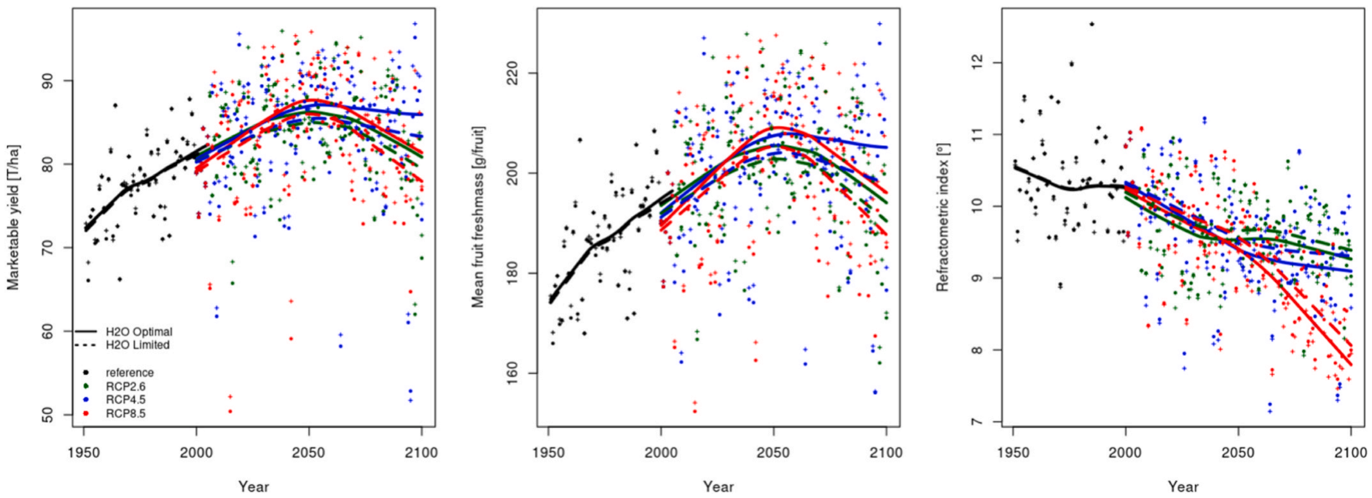

Fig. 5. Evolution of marketable yield, mean fruit fresh mass and refractometric index for the reference period (1950–2005) and three climate change scenarios (RCP 2.6, 4.5 and 8.5) during the period 2005 to 2100, in the Avignon region (Southeast France). Points are individual years (open circle for optimal irrigation; small point for limited irrigation), and lines reflect the general trend for each scenario/irrigation (optimal: solid line; water restriction: dotted line).

Table 3
Coefficient of variation (CV), minimum (Min), mean (Mean) and maximum (Max) values of the ecosystem service indicators computed on 716 simulations, and average values for the reference scenarios with optimal irrigation and RCP 8.5 with limited irrigation.

Indicator (unit)	CV (%)	Min	Mean	Max	Reference	RCP 8.5
Ymarket (t ha^{-1} year^{-1})	+8.39	50.41	82.62	96.81	77.92	82.35
BRIX (°BRIX)	+8.53	7.15	9.61	12.54	10.38	9.36
varN (kg N-humus ha^{-1} year^{-1})	−47.32	−126.81	−45.60	2.76	−27.72	−46.94
mNO3 (mg N-NO_3^- kg^{-1} of dry soil)	+35.70	1.00	2.46	6.95	1.80	3.13
tN2O (kg N-N_2O ha^{-1} year^{-1})	+34.96	0.36	0.86	2.33	0.59	0.99
Cfix (t C ha^{-1} year^{-1})	+12.89	1.04	2.74	3.68	2.72	2.84
mWC (g water cm soil^{-3})	+8.59	12.19	22.73	24.59	23.67	21.03
drain (mm year^{-1})	+167.95	0	29.07	406.52	30.18	9.83
tNleach (kg N-NO_3^- ha^{-1} year^{-1})	+158.62	0	1.07	10.12	1.08	0.39

despite the incorporation of leafy shoots in the soil, the soil needs an additional organic supply to maintain its organic nitrogen content. In fact, this indicator was highly variable within the dataset (coefficient of variation: −47.3%; Table 3), ranging from −126.8 to 2.8 kg N-humus ha^{-1} year^{-1}, depending on the scenario. Moreover, it showed autocorrelation among years for all the climate change scenarios, except for the RCP4.5 with limited irrigation amounts (Supplementary Material Table 2). In contrast, mean soil nitrate content at a depth of 0–30 cm was largely increased by both climate change (up to 39% for the RCP 8.5 scenario) and irrigation strategy (Fig. 6). In those scenarios with irrigation reduction, nitrate concentrations increased (Supplementary Material Table 2). These time series were autocorrelated except for those of the reference period and those with irrigation restrictions under the RCP 2.6 and RCP 4.5 scenarios.

3.3.3. Climate regulation

Regarding the ecosystem service of climate regulation, carbon sequestration by the orchard ranged from 1 to 3.7 t C ha^{-1} year^{-1} (Table 3). This indicator remained stable regardless of the climate change scenario, except for the worst scenario after 2050 (Supplementary Material Fig. 4). This relative stability is caused by two partially opposing effects: an increased growth in the perennial organs of the tree, up to 10% greater in the RCP 8.5 (Supplementary Material Fig. 5); and a decrease in the carbon sequestered in the soil with the severity of climate change. Moreover, irrigation limitation by reducing mineralization led to a positive effect on C sequestration by the apple orchard (Fig. 6, Supplementary Material Table 2 and Fig. 4). The increased growth in the perennial organs of the tree was related to the tree's photosynthesis, which sharply increased over the years regardless of the scenario, including during the reference period (Supplementary Figure 3). This increase was very strong and regular until the 2050s, and then slowed down or even leveled off in the RCP2.6 scenario. The C uptake by the tree increased by up to 14%, 27% and 42% for the RCP 2.6, 4.5 and 8.5 emission scenarios, respectively. Tree photosynthesis was only slightly affected by irrigation reduction. All the data series were autocorrelated.

The emissions of N_2O from the soil increased with the severity of climate change scenarios (Fig. 6). From 2050 onwards, these emissions were boosted in the case of RCP 8.5 (Fig. 6), the magnitude of this increase being 68% (Supplementary Material Table 2). Nitrification transforms NH_4^+ and NH_3 into NOx (NO_2^- and NO_3^-), with a fraction of the nitrogen that goes into N_2O emissions under aerobic conditions. Under anaerobic conditions, denitrification returns nitrogen to the atmosphere in its molecular form (N_2), with CO_2 and nitrous oxide (N_2O) as by-products. Both processes are increasing with global change, but it is mainly the denitrification process that is greatly increased (by up to 350%) according to our simulations (Supplementary Material Fig. 6). The N_2O emissions time series showed autocorrelation, except for the reference scenario. (Supplementary Material Table 2).

3.3.4. Water cycle maintenance and regulation

Finally, concerning water cycle maintenance and regulation, as expected, climate change scenarios only affected mean soil water content in the 0–30 cm layer when irrigation did not fulfill the tree water requirements. In that case, mean soil water content sharply decreased from 2005 onward (Fig. 6; Supplementary Material Table 2). Overall, the coefficient of variation of this indicator was lesser than 10% within the dataset (Table 3). Most of these time series were not autocorrelated.

Drainage and nitrate leaching were predicted to slightly increase over time for the three climate change scenarios, with a larger increase from 2050 onward in the case of the RCP 8.5 scenario (Fig. 6, Supplementary Material Table 2). The variability of both indicators was high, with coefficients of variation around 165% (Table 3). As expected, drainage and leaching decreased with the limitation in irrigation (Fig. 6).

4. Discussion

4.1. Improvements to QualiTree and testing of the model

The modeling approach presented in the current study allowed us to consider the impact of a range of climate change scenarios on a variety of ecosystem services provided by apple orchards. QualiTree was chosen and upgraded for this purpose, achieving a capacity to describe perennial systems with a degree of complexity rarely reached in models (Grisafi et al., 2022).

An additional benefit of this study was that the model outputs were successfully compared to field observations for a given season, which increases the reliability of the simulations performed. Specifically, this upgraded version of QualiTree satisfactorily reproduced the observed fruit and vegetative growth (both in fresh and dry mass). The model was capable of reproducing the observed concentrations of soluble solids and starch in the fruit flesh, and the dynamics of plant state variables such as plant water potential. It was able to accurately simulate the dynamics of soil water content over the growing season, capturing the progressive drying of soil after rainfall and irrigation events despite overestimations for the surface layer (0–10 cm) during the first part of the growing season.

Concerning the ecosystem service indicators, QualiTree outputs agreed with the values reported in the literature. Marketable yields were comparable to those obtained in apple orchards with low pest incidence (between 15 and 90 t ha^{-1} year^{-1}; Chen et al., 2024; Espinoza-Meza et al., 2023; Peck et al., 2006; Sharma et al., 2021). The values of the fruit refractometric index obtained in the simulations were in accordance with previous studies on the Golden Delicious cultivar (e.g., 8.7–15.9 in Ventura et al., 1998). The concentrations of nitrate in the 0–30 cm soil layer were of the same order of magnitude as those reported in previous studies (Neilsen and Neilsen, 2003; Oliveira et al.,

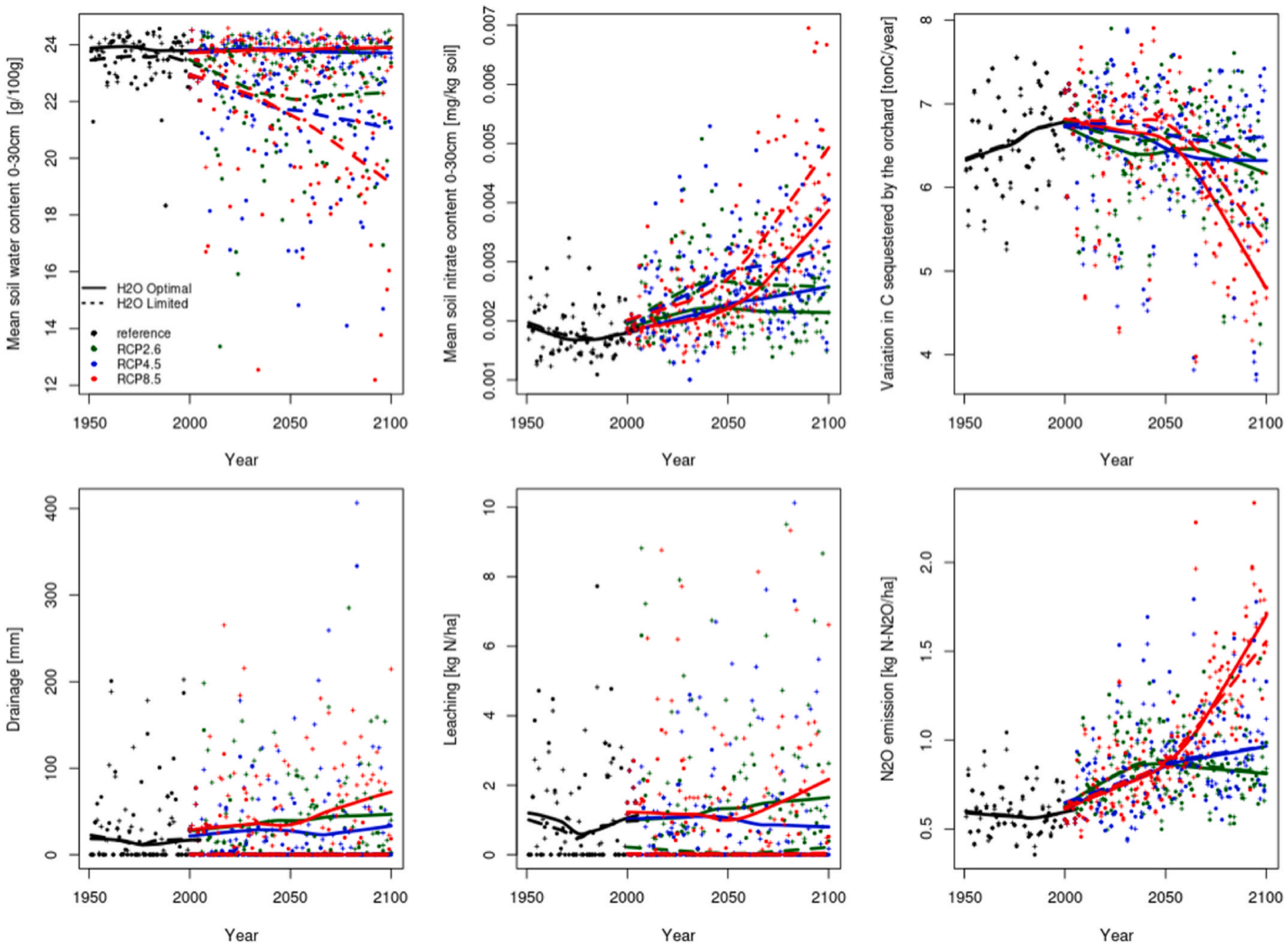

Fig. 6. Evolution of mean soil water content (0–30 cm), mean soil nitrate content (0–30 cm), variation in C sequestered by the orchard, drainage, nitrate leaching and N_2O emissions for the reference period (1950–2005) and three climate change scenarios (RCP 2.6, 4.5 and 8.5) during the period 2005 to 2100, in the Avignon region (Southeast France). Points are individual years (open circle for optimal irrigation; small point for limited irrigation) and lines reflect the general trend for each scenario/irrigation (optimal: solid line; water restriction: dotted line).

2016). Nitrous oxide emissions simulated by QualiTree were within the range of values previously measured in orchards (−0.116 to 26 kg N-N_2O ha^{-1} year^{-1}, as reviewed by Gu et al., 2019; 2.4 kg N-N_2O ha^{-1} year^{-1}, as observed in an apple orchard by Pang et al., 2019). The values reported by Pang et al. (2019) are from the semi-arid loess plateau of China and are at the lower end of the range of values reviewed by Gu et al. (2019). The predicted decrease by the model of the N_2O emissions as soil water availability decreases is consistent with these results. The amount of carbon fixed by the simulated apple orchard agreed with values reported in carbon balance investigations performed in fruit orchards, and was similar to the Net Ecosystem Productivity values reported by Montanaro et al. (2017), Panzacchi et al. (2012), Plénet et al. (2022) and Zanotelli et al. (2015, 2013) for apple or peach orchards, ranging from 2.2 to 7.6 Mg C ha^{-1} year^{-1}. Nitrate leaching was low in the simulations, ranging from 0 to 5 kg N-NO_3^- ha^{-1} for the reference period, and consistent with previous reports (Atucha et al., 2011; Ventura et al., 2013).

Our study focused on apple orchards in the Mediterranean region, but this work can obviously be extended to other geographical areas with different climates. The qualitree model was initially developed for peach trees (Lescourret et al., 2011) and can be adapted to other stone or seed fruit species. However, depending on the species and the geographical area, it will be important to further develop certain processes, in particular with regard to cooling requirements, frost and fruit sunburn damage.

4.2. Impacts of climate change and plant functioning

Despite referring to a given site, the projections used in the current study reflected the expected impact of increasing atmospheric CO_2 concentrations for the Mediterranean area, namely, a marked increase in temperature, which augments reference evapotranspiration (Iglesias et al., 2011). These conditions will raise crop water requirements, especially for fruit trees that, due to the expected increase in water demand from other sectors (industry, households, tourism, etc.), could lead to a risk of conflict for water use (Iglesias et al., 2011; Kavand et al., 2023).

Regarding plant functioning, our simulations predicted a progressive increase in the vegetative growth of the tree, regardless of the climate scenario, this increase being maximal for the RCP8.5 scenario. The increase in growth is associated both with the increase in atmospheric CO_2 concentration and, to a lesser extent, with the increase in temperature. The maximum leaf photosynthesis (Amax), i.e., with saturating radiation, is sharply increased. It has been suggested that long-term natural responses to increasing CO_2 will probably to be less drastic than what has been reported in short-term experiments where plant–soil and/or plant–atmosphere connections have been decoupled (Körner, 2006). However, a long-term experiment on apple (Lee et al., 2023), 8 years with 650 ppm CO_2, reported Amax values of more than double when compared to those measured at ambient CO_2 concentration. The increase in temperature slowed down this trend, with a negative effect on photosynthesis above a certain threshold since it was simulated for the worst-case scenario after 2050 in the current study. It has been shown that a marked increase in CO_2 concentration alone (650 ppm) leads to a sharp increase in shoot growth, whereas if this increase in concentration is combined with an increase in temperature (+5 °C), there is no effect on growth compared to the control (Lee et al., 2023).

The effect of climate change on fruit growth followed a typical bell-shaped curve, with a gradual increase in yield up to the 2050s, followed by a gradual decrease thereafter. Only in the case of the RCP 4.5 scenario, according to the simulations, yield did not decrease after this date, but it levelled off. The increase in temperature led to a significant shortening of growth duration, both for leafy shoots and for fruit. Thus, the fruit growth duration was reduced by more than 20 days between the reference period and the end of the century for the RCP8.5 scenario (Supplementary Material Fig. 2). Peach trees subjected to high temperatures (+5 °C compared to the control during the season) experienced an earlier slowdown in their development and vegetative growth, i.e., leaf emergence and axis elongation (Adra, 2017). The positive effect of the rise in CO_2 on photosynthesis did not result in a large increase in tree dry mass because of the deleterious effect of high temperatures on photosynthesis but, instead, because of this shortening of the phenological cycle. According to the functional equilibrium assumption in Qualitree, the tree seeks to reach a target shoot/root ratio value (Lescourret et al., 2011). The decrease in the leafy shoot biomass is therefore associated with a decrease in the growth of fine roots.

The effect of water deficit on dry matter plant growth was limited in all emission scenarios, probably due to the assumptions on initial soil conditions. Irrespective of the scenario chosen, initial soil conditions at the start of the growing season were assumed to be saturated with water to field capacity by the end of winter, resulting in a large amount of available water. The water deficit occurs mainly in the second half of the season when vegetative growth is already complete and much of the fruit growth has also taken place.

A blooming sequential model was fitted, based on a chilling sub-model combined with a heating sub-model, to predict dormancy release and blooming. According to the simulations performed, the rise in temperature has an antagonistic effect on the chilling and heating requirements. Climate change obviously leads to a shortening of the forcing period since the heating requirement is met much earlier. However, the chilling requirement and, hence, dormancy release is satisfied much later (Legave et al., 2013). Overall, the simulated flowering date (around the beginning of April) remained relatively stable regardless of the scenario. However, this result is highly dependent on the species and varieties studied. Species with reduced cooling requirements have been shown to present large forward shifts in the blooming date (Funes et al., 2016). For the future, increasing risks of spring frost in early-blooming cultivars are foreseen, but since the blooming date of 'Golden Delicious' apple was not affected in our study, this risk was reduced with climate change. In addition, the temperature during the previous growing season can affect the intensity of floral induction (Wilkie et al., 2008), and may lead to irregular floral and poor fruit set (see review Kumar et al., 2024). It will be therefore important to take these processes into account in order to better describe the consequences of climate change on fruit production.

4.3. Impacts of climate change on ecosystem services provided by apple orchards

4.3.1. Fruit production

QualiTree estimated an increase in marketable yields of apples for the studied orchard until about 2050, when they either declined (RCP 2.6 and RCP 8.5) or stabilized (RCP 4.5). These results partially agree with previous studies in which positive impacts of climate change on apple yields have been reported (Stöckle et al., 2010; Li et al., 2020). Recently, an experimental study on young apple trees suggested that elevated CO_2 concentration (650 ppm) and elevated temperature (5 °C higher than the ambient temperature) promoted shoot growth and slightly increased fruit fresh weights (Lee et al., 2023), supporting the outputs of our simulations. In contrast, QualiTree predicted sharp declines in the refractometric index of the apples due to the severity of climate change, in accordance with experimental observations (Lee et al., 2023). Changes in cultural practices, particularly of the crop load management, can help to offset this decline in fruit quality. However, maintaining fruit quality will only be possible at the expense of an extra yield reduction. In addition, as summer temperatures may increase much more than the average annual temperature, the occurrence of fruit damage due to heat (sunburn …) is likely to increase. Sunburn damage is related to direct radiation and heat stress, which are not yet simulated for the fruit, and should also be focused on in a next step.

4.3.2. Soil nitrogen availability

The estimated increase in soil nitrate with the severity of the climate change scenario is probably related to the decrease in N uptake by the plant. Since the growth period of leafy shoots and fruit is reduced, the total amount of N allocated to these compartments is also reduced. Furthermore, since nitrogen was still taken up by the tree, there was negative feedback on nitrogen uptake due to the increase in nitrogen reserves in the fine roots. When the irrigation amount is reduced, there is less drainage (Hardie et al., 2022). Since tree growth as well as the overall nitrogen absorbed was only slightly affected, the soil nitrogen content expressed on a soil dry weight basis increased. However, even if the soil nitrate concentration was higher, the reduced drainage prevented N leaching regardless of the climate scenario, as observed in an apple orchard (Zhang et al., 2023).

4.3.3. Climate regulation

Soil carbon sequestration plays an essential function, not only in climate change mitigation but also in plant nutrient accessibility and soil fertility (Alonso-Serra, 2021). Therefore, there is a significant overall interest in soil carbon capture from atmospheric CO2 and sequestration in the soil via plants (Sharma et al., 2021). In our study, we only consider C sequestration associated with the apple tree, but the vegetation growing between the trees can substantially contribute to C sequestration. In a peach orchard, the above-ground C fixed by the grass in the inter-row was around 1 T Carbon/ha/year (Plénet et al., 2022). Temperature is an important factor controlling soil organic matter (SOM) turnover. The increase in air temperature might lead to a greater microbial activity and the increase in enzymatic activity rates, resulting in a quicker SOM turnover (Hansen et al., 2018). In addition, water plays a key role in regulating soil organic carbon (SOC) mineralization due to its impact on the dynamics of soil microbial communities (Soares et al., 2023). According to our simulations, a higher soil moisture caused by irrigation increases soil microbial activity, which may result in an increase in the decomposition of soil organic matter (SOM) and, therefore, in rising CO2 emissions (Jabro et al., 2008; Kochsiek et al., 2009). This greater microbial decomposition of SOM may lead to lower soil organic contents (Dersch and Bohm, 2001), which might alter the SOM decomposition mineralization rate since it has been proven that this process also depends on the content of SOC (Tan et al., 2014). According to QualiTree simulations, carbon fixation will increase overall in the orchard due to the increased growth of tree perennial organs (wood and roots), whereas decreases in SOC would be expected, probably due to the impact of elevated temperatures on SOM turnover. The dynamics of SOC will result from the balance between the respective increases in crop productivity and mineralization. If irrigation leads to a greater increase in productivity than in mineralization, then SOC will indeed increase.

Interestingly, our simulations suggested that reducing irrigation amounts would reduce the extent of this SOC decrease independently of the climate change scenario. Previous simulation studies suggested that apple orchards acted as carbon sinks within a mixed agroforestry catchment when subjected to climate change (Mirmasoudi et al., 2019), which agrees with the results of our study.

An important greenhouse gas emitted from agricultural lands and influenced by irrigation is N_2O (Trost et al., 2013). QualiTree outputs indicated that these emissions will increase between 40% and 69% on average, depending on the severity of the climate change scenario, compared to the baseline period. Nitrification and denitrification are the main processes for N_2O formation (Bremner, 1997; Phillips, 2008), and both soil moisture and temperature can influence these microbial processes. Increased soil moisture and temperature may cause a rise in the activity of nitrifying bacteria (Jha et al., 1996), but excess irrigation may lead to reduced soil aeration, resulting in low oxygen concentrations (anaerobic conditions) that support denitrification (Amha and Bohne, 2011; Ruser et al., 2006; Scheer et al., 2008). Climate change may therefore increase N_2O emissions mainly through an increase in soil temperature since, according to our simulations, the effect of soil moisture is small. However, the impact of irrigation practices cannot be underestimated. An increase in denitrification processes was observed when a previously identified critical threshold value of water-filled pore-space in the soil in irrigated olive groves was surpassed (Maris et al., 2015). In the context of the multiple interactions between the processes occurring in agroecosystems, the increase in N_2O emissions could reduce or negate the potential positive effect of improved carbon sequestration (Ball et al., 2008; Chatskikh and Olesen, 2007; Li et al., 2005; Smith et al., 2000). These results highlight the need to integrate knowledge into models such as QualiTree to achieve a better overall understanding of the functioning of fruit tree orchards.

4.3.4. Water cycle and maintenance

According to QualiTree outputs, the indicators involved in the water cycle and maintenance depended more on the irrigation amounts than on the severity of climate change. For instance, when irrigation covered the apple tree water needs, mean water content in the soil remained constant, independently of the climate change scenario considered. However, when irrigation was restricted to the water amount available in 2019, mean soil water content decreased with the severity of the climate change scenario (up to 11.2% for the worst-case scenario). Experimental works provided clear evidence of the relevance of irrigation strategies on the dynamics of soil water content that are in accordance with the outputs from the current study (e.g., Maris et al., 2015).

Drainage and leaching behaved differently depending on the irrigation amount. When it was enough to cover tree water requirements, both indicators increased with the severity of climate change scenarios (up to 65–70% in the worst-case scenario). However, when irrigation amounts were restricted, both indicators sharply decreased, up to 65–70% in the worst-case scenario. These results confirmed experimental observations (Baram et al., 2017) and highlighted the urgent need of adapting irrigation strategies to meet tree water requirements in order to reduce drainage and leaching, which may lead to contamination of groundwater bodies (Thompson et al., 2020).

4.4. Considering the perennial nature of the orchard: a future model perspective

Despite providing reliable estimates of several ecosystem service indicators under climate change conditions, our approach has the main limitation that it does not account for season-to-season carry-over effects, which are prone to occur in fruit trees as a response to abiotic stresses (Intrigliolo et al., 2013). To go further, as far as the long-term functioning of the soil in an orchard is concerned, we can draw inspiration from the generic crop models widely used to study the long-term effects of climate change on yield (e.g., Rosenzweig et al., 2013). This should not be an obstacle since QualiTree's soil module is based on that of one such model, STICS. Regarding the perennial nature of trees, attempts on modeling tree features (such as growth and mortality) in the long-term are scarce (Barbault et al., 2024), even for forest species (e.g., Pedersen, 1998; Rasse et al., 2001; Halpin and Lorimer, 2016). L-PEACH (Allen et al., 2005; Da Silva et al., 2014) is one of these attempts in the case of fruit trees. However, it adopts a very detailed view of the tree's architecture and development, which implies a high level of computing power that is restrictive for the very long-term simulations required in climate change studies (Grisafi et al., 2022). Moreover, this view is not necessary from an ecosystem service perspective. Our next challenge will be to find modeling options to represent, at the necessary and sufficient level of detail, the perennial nature of the orchard effects in order to take an in-depth look at the effect of driving forces such as climate change on bundles of services provided by orchards, in conventional or even agro-ecological frameworks such as agroforestry systems.

5. Conclusions

This work is, to our knowledge, the first attempt to use a fruit tree model to predict the impacts of climate change on a bundle of ecosystem services supplied by high water-requiring crops such as apple trees. An upgraded version of QualiTree was used in the current study. Interestingly, the simulations predicted a slight temporary increase in marketable yields with climate change. In contrast, a large decrease in the values of the refractometric index, a fruit quality trait, is expected as a consequence of more restrictive climate conditions. Regarding climate regulations, emissions of nitrous oxide were expected to increase due to a rise in denitrification rates, whereas C sequestration would increase in the perennial organs of the tree, but decrease in soil humus. Drainage and nitrate leaching would increase with the severity of climate change, especially from 2050 onwards, strongly depending on the irrigation management. Ultimately, this modeling study should help to take account of the impacts of climate change when designing orchard management systems.

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CRediT authorship contribution statement

Gilles Vercambre: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **José M. Mirás-Avalos:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Perrine Juillion:** Writing – review & editing, Investigation. **Mostafa Moradzadeh:** Writing – review & editing, Methodology, Conceptualization. **Daniel Plenet:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Pierre Valsesia:** Software, Methodology. **Mohamed-Mahmoud Memah:** Writing – review & editing, Supervision, Methodology. **Marie Launay:** Writing – review & editing, Conceptualization. **Vincent Lesniak:** Writing – review & editing, Data curation. **Bruno Cheviron:** Writing – review & editing, Data curation. **Michel Genard:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Francoise Lescourret:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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