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Insights into fruit tree models relevant to simulate fruit tree-based agroforestry systems

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Abstract Agroforestry, the integration of trees, crops, and animals, is expected to increase environmental sustainability of fruit production compared to traditional orchards. Virtual experiments with models would allow the performance and sustainability of these systems to be evaluated in a range of pedoclimatic and management scenarios, taking into account the interactions of fruit trees with crops. The models should represent tree and crop growth in 3D, run simulations over the whole life cycle of the orchard, and account for management practices that influence tree-crop interactions. We reviewed existing fruit tree and agroforestry models and have proposed a decision tree to guide future modellers in choosing a model that meets their simulation objectives. None of the reviewed models met all requirements, but we identified improvements that could be made to two existing models to accurately simulate temperate fruit tree based agroforestry systems.

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Abbreviations

PAR	Photosynthetically active radiation
HI	Harvest index
FSPM	Functional structural plant model
GPP	Gross primary production
NPP	Net primary production
FT-AFS	Fruit tree-based agroforestry systems

Introduction

Agroforestry was defined more than 40 years ago (Bene et al. 1977), and this definition has evolved to include a wide range of agroforestry systems with diverse objectives assigned to them (Somarriba 1992). This definition has recently been adjusted to include the context of climate change and the need to connect economic, social and political dimensions (Lauri et al. 2019; van Noordwijk 2018). In this sense, USDA described agroforestry as "the intentional mixing of trees and shrubs into crops and animal production systems to create environmental, economic, and social benefits" (USDA Agroforestry Strategic Framework 2011). Every EU Member State recently included its own definition of agroforestry within its Common Agricultural Policy Strategic Plan (Lawson 2023).

In the global warming context, agroforestry is one of the solutions that could help mitigate and adapt to climate change effects (Hernández-Morcillo et al. 2018). Regarding mitigation, agroforestry allows carbon sequestration, notably through the accumulation of carbon in the biomass and the soil, and favours the reduction of greenhouse gas emissions, notably through the reduction of N_2O emissions due to a better absorption of nutrients (Hernández-Morcillo et al. 2018; Jose 2009). About adaptation, agroforestry increases the resilience of systems and biodiversity (Lawson et al. 2023; Rolo et al. 2023; Hernández-Morcillo et al. 2018; Jose 2009; Quinkenstein et al. 2009; Wolz & DeLucia 2018).

Agroforestry can be subdivided into 11 sub-practices: (i) Silvopastoral, (ii) forest grazing, (iii) wood pasture or orchard grazing, (iv) silvoarable, (v) forest farming, (vi) alley cropping, alley coppice, or orchard intercropping, (vii) agrosilvopastoral, (viii) sequential mixtures of silvoarable and silvopastoral systems, (ix) linear agroforestry, (x) forest strips, (xi) shelterbelt networks, wooded hedges or riparian tree strips (Dupraz et al. 2018a, b). In agroforestry systems, trees may have different functions. In some cases, they mainly produce a service to the underlying crop (e.g. shade trees in coffee or cocoa-based agroforestry systems) or they have an objective of production (timber, fuelwood, cork, etc.) that is considered as secondary to the production of crops. Alternatively, they can constitute the main production expected on the plot, and crops or animals constitute a complementary production. The latter case is termed "high-value-tree agroforestry" (Deng et al. 2017). In the EU, these systems would be called "permananent-crop-agroforestry" and all land in the category of "permanent crops" automatically qualifies for CAP (Common Agricultural Policy) Basic Payments. These systems are usually based on trees producing fruits or nuts such as, in temperate and Mediterranean climates, olive, apple, pear, walnut, chestnut, hazelnut, which constitute the principal source of income (Pantera et al. 2018)

These fruit trees based agroforestry systems provide several benefits for tree growers. For example, they allow diversifying the production, thus increasing resilience towards climatic or economic changes, while at the same time increasing the total production of the agricultural plot compared to separate orchards and annual crops (Zahoor et al. 2021). Another benefit can be an increase of soil fertility, in particular through nitrogen fixation by legume crops (Dollinger and Jose 2018). Other benefits include increased pollination (Bentrup et al. 2019), improved natural regulation of pests (Pumariño et al. 2015) or improved infiltration and water retention capacity of the soil (Wang et al. 2017). They also provide other ecosystem services such as carbon sequestration (Ramachandran Nair et al. 2010) or biodiversity conservation (Torralba et al. 2016).

However, the benefits for both production and ecosystem services provision are dependent on the design and management of agroforestry systems, in particular the choice of species, the spatial organisation of the plot as well as tree and crop management: including soil tillage, fertilisation, irrigation, tree pruning, etc. These factors also interact with the soil and climate conditions, and the ecological conditions in which the system is embedded. Thus, there is no one-size-fits-all agroforestry system, and the system has to be adapted to the environmental conditions as well as to the farmer's objectives and constraints.

Several approaches can be used to test different systems and compare alternative solutions. These can be tested through on-station and on-farm experiments. However, these experiments are expensive in terms of time (trees grow slowly), space (trees are widely spaced and need controls), manpower for monitoring these trials and financial costs. The designs must also be replicated in many geographical sites to test the resilience of the system in response to soil and climate constraints or to adapt systems to local pedoclimatic conditions. An alternative solution is to perform virtual experiments using computer models which simulate the impact of cultural practices on the development of the tree and its productivity (Vos et al. 2007).

A recent literature review by Grisafi et al (2022) synthesised the diversity of models that have been developed for fruit trees (Grisafi et al. 2022). They showed that: (i) modelling of the fruit tree architecture improved the reliability of the simulations, (ii) spatially explicit models allowed the simulation of the canopy dynamics as well as the light interception dynamics, (iii) FSPM models allow a good understanding of the functioning of the tree architecture. However, their review focused on modelling of trees in monospecific orchards. They did not address the suitability of the models for agroforestry systems based on fruit trees. Due to the current challenges facing fruit production worldwide (adaptation to climate change, reduction of negative environmental impacts, protection of consumers' and agricultural workers' health, etc.), agroforestry systems might become more important in horticultural production, and the need to model these systems will become more and more pressing (Grisafi et al. 2022). There is a wide diversity of existing models for orchards, however few are able to simulate agroforestry systems, since the processes driving tree-crop interactions and/or processes impacted by tree-crop interactions are not always represented in simple fruit-tree models. Focusing here on temperate fruit trees, we have reviewed existing models to identify those that could be adapted to represent the functioning of fruit tree-based agroforestry systems (FT-AFS).

This paper will address three main questions: (i) which processes should be implemented to represent the functioning of fruit tree-based agroforestry systems?; (ii) are current fruit tree models suitable for simulating the functioning of FT-AFS?; (iii) are current agroforestry models suitable to simulate the functioning of FT-AFS? In the discussion, two main questions are considered: (i) how to choose the most suitable model to answer one's scientific question? (ii) how to adapt existing models to simulate the functioning of FT-AFS?

Modelling: what are the key elements of FT-AFS to represent?

To simulate FT-AFS, a number of processes need to be represented. All soil–vegetation–atmosphere transfer (SVAT) processes, such as water balance or energy transfers, are required in order to predict the plants (trees and crops) responses to the environmental conditions. Those processes are included in most crop models, such as the STICS model (Brisson et al. 2009), the APSIM model (McCown et al. 1996), the Hi-sAFe model (Dupraz et al. 2019) or the OliveCan model (López-Bernal et al. 2018). But in addition, processes that are specific to agroforestry systems should also be taken into account. These include the processes driving or being driven by tree-crop interactions, such as competition, complementarity or facilitation (Vandermeer 1989) (Fig. 1).

Regarding the environment, it is necessary to consider variables describing climatic and soil conditions of the plot to be simulated. Climate is generally represented by daily input variables such as average air temperature (and/or minimum and maximum

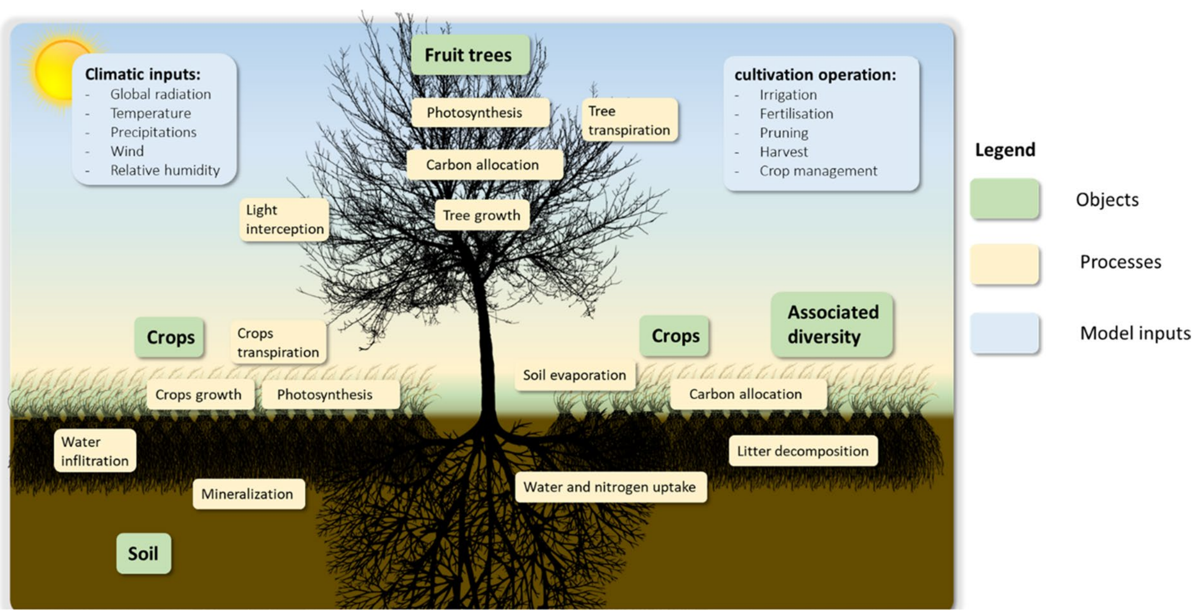


Figure 1 Processes to represent when simulating the functioning of FT-AFS.

temperatures), precipitation, global radiation and wind. To simulate soil, several variables can be considered, such as soil depth, texture, pH, organic matter content, microbial biomass, humidity, nitrate and ammonium content, etc.

In order to be able to represent tree-crop interactions, agroforestry models have to represent the components of the system that drive these interactions. Thus, they cannot focus only on fruit production, as some empirical fruit tree models do, but should also consider the tree vegetative growth, because vegetative organs drive the competition between trees and crops (light competition for the aerial part, and water and nutrient competition for the belowground part). Similarly, for crops, it is important to represent both the aerial and belowground parts of the plants. Indeed, the crop canopy will drive not only light interception and transpiration by the crop but also evaporation from bare-soil. These processes will affect the soil water availability and ultimately the tree growth. Furthermore, the tree and crop foliage has to be at least partly spatially explicit because tree-crop interactions are driven not only by the biomass of the respective species, but also by the spatial configuration of the system (Jiménez and Díaz 2003). Furthermore, the rooting profile of the crops and trees must be explicitly represented since is essential to evaluate the intensity of tree-crop competition for water and nutrients. At the same time, competition for water and nutrients will vary according to distance from the tree, and light competition will also depend on orientation relative to the tree. Therefore, the model should represent space in 3D to consider both the spatial heterogeneity of agroforestry systems (2D) and the dominance or complementarity along the vertical axis.

Another important feature of agroforestry systems is the temporal complementarity between trees and crops (e.g. winter crops using resources in winter when trees are leafless in temperate regions), and trees using resources in summer (after winter crop harvest). Furthermore, some of the expected ecosystem services produced by cover crops, or even cash crops, are dependent on the period at which the crop is sown or harvested (e.g. reduction of erosion, which is important at periods of high rainfall, in particular in Mediterranean climate). Therefore, to be able to capture the interplay between the crop's and the tree's phenologies, and the weather variability during the year, it is important to simulate the system with a sufficiently high temporal resolution. However, it is also important to represent the system over a long period, because tree-crop interactions evolve over many years as trees grow, and there is a feedback between tree-crop interactions and tree growth. Therefore, it is not possible to use fixed-size trees: tree size and its change with time is an endogenous variable in the system.

The models should also integrate the key tree cultural operations that have an impact on the tree-crop interactions, such as: irrigation, fertilisation, branch and root pruning, soil tillage and fruit load management. Similarly, crop management practices that might have an impact on trees are sowing and harvest dates, soil tillage, irrigation, fertilisation. Indeed, irrigation drives the impact of water competition (if there were sufficient water for both crops, competition would not be felt), fertilisation drives the impact of nitrogen competition, soil tillage drives belowground competitions by destroying roots at regular intervals and tree pruning drives light competition. In case of interactions between weeds, diseases, pests or beneficial organisms of the tree and of the crop, management practices aiming at controlling pests (*sensu lato*) should also be considered.

The (positive and negative) interactions between the fruit tree and the understory crop will then result from the simulated processes: water uptake by the tree and the crop will lead to competition for water, light interception by the tree trunk and canopy will cause competition for light, the buffered microclimate under the tree might create more favourable conditions for the crop, resulting in facilitation, nitrogen released by decomposition of legume crop residues will improve nitrogen nutrition of the tree etc. More direct interactions could also be simulated when necessary, such as allelopathy in the case of walnut trees, although this seems to be limited in agroforestry systems (Inderjit and Nilsen, 2003).

These processes allow representing of the competition and/or complementarity (for light, water, nutrients), and facilitation-processes (buffered microclimate, improved fertility, modified and deeper root profiles) between trees and crops. Carbon allocation is integrated in the fruit-carbon compartment.

To summarise, compared to models that focus only on fruit production, models aiming at simulating fruit trees in agroforestry systems should have the following features:

- represent space in 3D with a spatial scale relevant to tree-crop interactions
- represent time with a sufficiently long time period to model tree growth (typically several decades), and a sufficiently fine time step to represent the complementarity between tree and crop phenologies (typically days or hours).
- represent the four most important cultural operations impacting on tree-crop interactions: irrigation (driving the impact of water competition), fertilisation (driving the impact of nitrogen competition), fruit load management (driving belowground competitions) and tree pruning (driving light competition).

Bibliographic study: defining the focus on fruit tree and agroforestry models

Since the literature search is focused only on models integrating temperate fruit species, tropical fruit tree models are not included, although it is likely that some mechanisms used in tropical models are also relevant for temperate fruit tree models. It is also important to note that specific formalisms can could be identified in environmental models (e.g., models focused on light interception, etc.). This However, this review article does not explore the available models for each specific process but focuses solely on available agroforestry and fruit tree models.

To identify fruit tree models in the literature, we relied on existing literature reviews such as Grisafi et al. (2022) and Moriondo et al. (2015). The list of existing models was completed by specific searches (on Web of Sciences and GoogleScholar search engines) with: "olive tree modelling", "apple tree modelling", "pear tree modelling", "peach tree modelling". This search was based on the highest economic value species in the temperate and Mediterranean regions.

To identify the different agroforestry models in the literature, we relied on existing literature reviews such as Burgess et al. (2019) and Kraft et al. (2021). The list of existing models was completed by specific searches (on Web of Sciences and GoogleScholar search engines) with: modelling agroforestry systems, modelling diversified systems.

Models' diversity: very different modelling objectives

A synthetic view of different fruit-tree and agroforestry models

During the last 50 years, several models have been developed by researchers to understand, predict, or optimise the functioning of trees (Fig.2). Built to address various problems, these models are based on different methodologies, with various degrees of simplification. In the literature, fruit and agroforestry models have been developed in parallel: no agroforestry model was initially developed with fruit trees in mind (but some have been adapted afterwards (e.g. Palma et al. 2016)).

For fruit trees, models can be classified into two categories: empirical models based statistical relationships and mechanistic models. Mechanistic models can be separated into two subcategories: (i) "fine-scale architecture": FSPM (Functional Structural Plant Models models) which are based on a detailed representation of tree architecture, (ii) "coarse architecture" scale models: compartmental models, which are based on a rougher representation of tree structure. FSPM models represent the architecture of the plant, by dividing the plant into different elementary parts that have an explicit position in space, at least relative to the other components. Biophysical process-based models represent the development of the plant according to the interaction of several physical and/or biological processes acting on compartments of the plant that are not necessarily positioned in space (Sievänen et al. 2014).

For agroforestry systems, various models have been developed with different formalisms. Six types of models predominate (Burgess et al. 2019): (i) allometric models, (ii) non-growth models of soil carbon or light interception, (iii) plot scale models of tree and crop growth, (iv) architectural models at the plant scale, (v) farm decision models, (vi) landscape models. In this article, only plot scale models of tree and crop growth are developed, because they possess the three characteristics that we identified as essential for

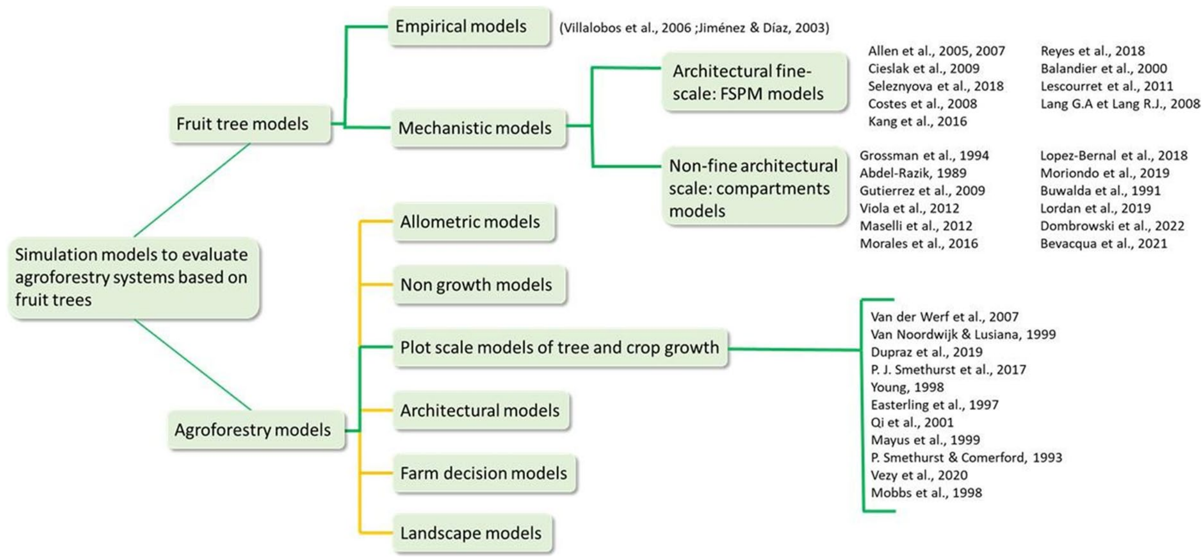


Figure 2 A synthetic view of different fruit and agroforestry models presented in this review. The green lines illustrate the models developed to simulate the growth and yield of fruit tree in a conventional or agroforestry context. The yellow lines indicate the coexistence of other types of models not considered here.

simulating the functioning of FT-AFS, while remaining relatively simple.

Focus on the diversity of fruit tree models

In the literature, fruit models have been developed for various species such as apple trees (*Malus domestica* L.), peach trees (*Prunus persica* L.), olive trees (*Olea europaea* L.), pear trees (*Pyrus communis* L.), walnut trees (*Juglans sp.* L.), cherry trees (*Prunus avium* L.) and kiwi trees (Actinidia) (Table 1). Representation-methods differe according to the objectives of the model.

Empirical fruit tree models

Empirical models are based on a set of equations linking explanatory variables with one or several response variables. The model is a "black box": the modeller does not need to know why these variables are related, just that empirical evidence (often based on statistical analysis of field data) shows a relationship between the variables.

We found only two empirical models: one for olive trees developed by Villalobos et al. (2006) and a second for pear trees built by Jiménez and Díaz (2003). However, other empirical models might exist and have not been listed in this review because they are not presented as "models" in the literature.

These two fruit tree models are based on empirical relationships and do not consider physical and biological processes. This type of model can be used by farmers to predict their future yield as a function of variables measured before flowering (Jiménez and Díaz 2003) or by researchers to understand the components of yield most impacted by environmental conditions (Villalobos et al. 2006), but they are unable to predict the development of a tree in a new agroecosystem, as the model's parameters would need to be calibrated again in each environment.

Architectural fine-scale: functional structural plant models

Functional Structural Plant Models (FSPM) simulate the plant growth and development. The model simulates the photosynthesis and/or respiration of each organ individually (according to the scale studied), their growth, and the relationships between organs. FSPM models are often used to understand the links between the architecture and the development of the plant. These plant-centred models represent a real advance, in understanding carbon-allocation dynamics, over empirical models. Initially developed on

Table 1 Summary of the different fruit tree models according to the species modelled.

Species	Model (if named)	Bibliography
Apple trees		Seleznyova et al. (2018)
Apple trees	MAppleT model	Da Silva et al. (2014a, b
Apple trees	MaluSim	Lakso et al. (1999)
Apple trees	IMApple	Kang et al. (2016)
Apple trees	MUSCA	Reyes et al. (2018)
Apple trees	CLM5-FruitTree	Dombrowski et al. (2022)
Cherry trees	VCHERRY	Lang and Lang (2008)
Kiwi trees	L-Kiwi model	Cieslak et al. (2011a, b)
Kiwi trees		Buwalda (1991)
Olive trees		Abdel-Razik (1989)
Olive trees		Villalobos et al. (2006)
Olive trees		Gutierrez et al. (2009)
Olive trees		Viola et al. (2012)
Olive trees		Maselli et al. (2012)
Olive trees		Morales et al. (2016)
Olive trees	OliveCan	López-Bernal et al. (2018
Olive trees		Moriondo et al. (2019)
Peach trees	L-PEACH	Lopez et al. (2010)
Peach trees	PEACH	Grossman and DeJong (1994)
Peach trees	Qualitree	Lescourret et al. (2011)
Peach trees		Bevacqua et al. (2021)
Pear trees		Jiménez and Díaz (2003)
Walnut trees	SIMWAL	Balandier et al. (2000)

annual crops, FSPM models have been developed for perennial crops such as fruit trees. To go from annual to perennial species, several new processes had to be added: (i) the specific phenology (senescence, bud break) of fruit trees, (ii) the carbon reserve compartment (storage and remobilization) and (iii) the formation of new organs (in the buds) during the previous year. The carbon dynamics in the plant had to be modified accordingly. For fruit trees, representation-methods are different in comparison with annual crops and often more complex. These models aim to better understand and define the effect of pruning and fruit load on the fruit tree.

In the literature, several FSPM have been developed to simulate the architecture of temperate fruit trees (e.g. peach, kiwi, walnut, cherry, and apple). We will focus here on the comparison between these models, the description of each individual model is available in the Supplementary Information A. These nine FSPM fruit trees models are: L-Peach, L-Kiwi, Apple, MAppleT, IMApple, MUSCA, SIMWAL, QualiTree, VCHERRY.

These models represent the development of a fruit tree according to more or less divergent formalisms depending on the processes (photosynthesis, the root system, the inter-annual fruit production variability, the inter-annual tree growth) (Table 2). All reviewed FSPM models represent photosynthesis. Indeed, this process is the basis of carbon synthesis. It can be simulated by two biogeochemical approaches: (i) the Farquhar-von Caemmerer-Berry (FvCB) model, (ii) the photosynthesis-light response curve. The FvCB model describes the biological functioning of photosynthetic mechanisms. More precisely, the parameters of these mechanisms require a very accurate calibration. The photosynthesis-light response curve does not describe biological functioning. Consequently, its calibration is easier. The L-Peach, the MUSCA and the SIMWAL models use the FvCB model. In contrast, the L-Kiwi, the Apple and the QualiTree models apply the photosynthesis-light response curve.

The root system is also present in all models. However, depending on the model, the root architecture system is more or less simplified. Furthermore, some models, such as Apple model and VCHERRY model, take into account the rootstock, which influences carbon allocation to roots, tree vigour, growth and flowering (Gjamovski and Kiprijanovski 2011; Lauri et al. 2006). The inter-annual variation in fruit production is rarely considered. Nevertheless, the dynamics of production is fundamental to represent the phenomena of production irregularity in fruit trees. In the model descriptions, limited information is provided on this aspect. The SIMWAL and QualiTree models do not simulate several years of production.

Depending on the model, management practices differ (Table 3). As the main objective of FSPM models is to understand carbon allocation in the plant, all the examined FSPM models take into account pruning as a cultural operation. The impact of fruit load is also widely studied with FSMP models. This practice is represented in all models, except the SIMWAL model. Irrigation and fertilisation of fruit trees seem to be poorly represented in the models studied. For irrigation, only the QualiTree and L-Peach models are able to test the effect of irrigation on tree development. Fertilization is never mentioned in model descriptions. None of these models can represent

Table 2 Summary of the different formalisms of fruit trees FSPM models (Functional Structural Plant Models).

Model	Publications	Roots	Rootstock	Fruit compartment	Inter-annual fruit production	Inter-annual tree growth	Photosynthesis
L-Peach	Allen et al (2005, 2007) Smith et al. (2008) Lopez et al. (2010) Da Silva et al. (2014b)	Yes	No	Yes	No indication	No indication	Farquhar-von Caemmerer-Berry (FvCB)
L-Kiwi	Cieslak et al. (2009) Cieslak et al. (2011a, b) Cieslak et al. (2011a, b)	Yes	No	Yes	No indication	No indication	photosynthesis-light response curve
Apple	Seleznyova et al. (2018)	Yes	Yes	Yes	No indication	No indication	photosynthesis-light response curve
MAppleT	Costes et al. (2008) Da Silva (2014a) Pallas et al. (2016)	Yes	No	Yes	No indication	Yes	No indication
IMApple	Kang et al. (2016)	Yes	No	Yes	No indication	No indication	No indication
MUSCA	Reyes et al. (2018) Reyes et al. (2020)	Yes	No	Yes	No indication	No indication	Farquhar-von Caemmerer-Berry (FvCB)
SIMWAL	Balandier et al. (2000)	Yes	No	No	No	No indication	Farquhar-von Caemmerer-Berry (FvCB)
QualiTree	Lescourret et al. (2011)	Yes	No	Yes	No	No	photosynthesis-light response curve
VCHERRY	Lang and Lang (2008)	Yes	Yes	Yes	No indication	No indication	No indication

Table 3: Summary of the management practices taken into account in fruit trees FSPM models.

Model	Publications	Fruit load management: thinning	Pruning	Irrigation	Fertilisation
L-Peach	Allen et al. (2005, 2007) Smith et al. (2008) Lopez et al. (2010) Da Silva et al. (2014b)	Yes	Yes	Yes	No indication
L-Kiwi	Cieslak et al. (2009) Cieslak et al. (2011a, b) Cieslak et al. (2011a, b)	Partially	Yes	No indication	No indication
Apple	Seleznyova et al. (2018)	No indication	Yes	No indication	No indication
MAppleT	Costes et al. (2008) Da Silva et al. (2014a) Pallas et al. (2016)	Yes	Yes	No indication	No indication
IMApple	Kang et al. (2016)	Yes	Yes	No indication	No indication
MUSCA	Reyes et al. (2018) Reyes et al. (2020)	No indication	No indication	No indication	No indication
SIMWAL	Balandier et al. (2000)	No	Yes	No	No
QualiTree	Lescourret et al. (2011) ; Mirás-Avalos et al. 2013 ; Mirás-Avalos et al. 2011	Yes	Yes	Yes	No indication
VCHERRY	Lang and Lang (2008)	Yes	Yes	No indication	No indication

cropping under trees. Simulation periods are rarely presented, but rarely exceed 1 or 2 years.

One strong limitation of FSPM is that the generally short time step (minute or hour) prevents simulation of the development of the tree from the plantation to the end of its life. The representation of all the organs generates huge datasets for an adult tree that require high computation resources. Therefore, these models tend to be used to simulate only young trees. Another limitation of these models is that they do not consider the environment in which the tree evolves, apart from incident radiation. And yet, biotic and abiotic constraints, as well as management practices, have a direct effect on vegetative development as well as on fruiting and fruit development.

Coarse architectural scale: compartments models

Coarse architectural scale models (or compartments models) often take the form of compartments, where all organs of a certain type are pooled (i.e. contrary to FSPM, the architecture is not taken into account explicitly). The number of organs or the biomass in each compartment are the state variables, and fluxes of matter between the different compartments are driven by equations supposed to represent the biological mechanisms. Mechanistic process-based fruit tree models have been developed since the 1990s on various temperate fruit tree species: peach, olive, kiwi and apple trees.

In the literature, several coarse architectural scale models have been developed since the 1990s to simulate the development of fruit trees (e.g. peach, kiwi, apple and olive). We will focus here on the comparison between these models, since the description of each individual model is available in the Supplementary Information B. These 12 non-fine architectural scale fruit tree models are those described in the following papers: (Grossman and DeJong 1994; Abdel-Razik 1989; Gutierrez et al. 2009; Viola et al. 2012; Maselli et al. 2012; Morales et al. 2016), Olive-Can (López-Bernal et al. 2018; Moriondo et al. 2019; Buwalda 1991; Lakso et al. 1999), CLM5-fruit tree model (Dombrowski et al. 2022; Bevacqua et al. 2021).

Similarly to FSPM models, coarse architectural scale models represent the development of a fruit tree according to more or less divergent representation methods depending on the mechanisms represented (Table 4). For photosynthesis representation, three models used Farquhar-von Caemmerer-Berry (FvCB) formalisms, four models used Photosynthesis-light response curve and the MaluSim model used another light model, the Charles-Edwards model, which calculates the interception of light by the plant under the assumption that the leaves are uniformly distributed (Charles-Edwards and Thornley 1973). The root system and the fruit compartment are present in all models. However, depending on the model, it can be more or less simplified.

The phenomenon of irregularity of production, which is often termed “alternate bearing” when displaying a typical ON–OFF fruiting pattern across consecutive years, is rarely discussed in the literature of fruit tree models. Due to multiple endogenous and exogenous factors causing it, the irregularity of production is difficult to predict. Only the CLM5-Fruit Tree model explicitly takes into account the dynamics of fruit production (inter-annual production). Some models do not take it into account the inter-annual production and for some of them no information is available in the literature. Only the CLM5-Fruit-Tree model is able to represent the dynamics of fruit production.

The fruit tree models also differ in terms of their representation of space. Only the models of Morales et al. (2016) and López-Bernal et al. (2018) are three-dimensional and allow representing some aspects of the spatial heterogeneity, which is an important feature of agroforestry systems. However, only the model of Moriondo et al. 2019 is able to represent cropping under trees. Simulation periods are rarely presented. Depending on the model, management practices are not always taken into account (Table 2). Some models do not represent management practices at all, such as landscape spatial scale models: Gutierrez et al. (2009) and Maselli et al. (2012). Although widely used in arboriculture, irrigation and fertilization are not necessarily represented in all models. Pruning or management of the fruit tree canopy is rarely represented: only the models by Abdel-Razik. (1989), Morales et al. (2016), López-Bernal et al. (2018), Dombrowski et al. (2022) and Bevacqua et al. (2021) incorporate them. Fruit load management through fruit thinning, rather than by pruning, is rarely represented in the models (except for the models developed by Grossman et al. (1994) and Bevacqua et al.

Table 4 Summary of the different formalisms of compartment fruit trees models.

Model	Publications	Roots	Rootstock	Fruits compartment	Inter-annual production	Inter-annual tree growth	Photosynthesis
	Grossman and DeJong (1994)	Yes	No	Yes	No indication	No indication	Farquhar-von Caemmerer-berry (fvcb)
	Abdel-Razik (1989)	Yes	No	Yes	No indication	No indication	Photosynthesis-light response curve
	Gutierrez et al. (2009)	Yes	Yes	Yes	No indication	No indication	Photosynthesis-light response curve
	Viola et al. (2012)	Yes	No	Yes	No indication	Yes	No indication
	Maselli et al. (2012)	Yes	No	Yes	No indication	No indication	No indication
	Morales et al. (2016)	Yes	No	Yes	No indication	No indication	Farquhar-von Caemmerer-berry (fvcb)
OliveCan	López-Bernal et al. (2018)	Yes	No	Yes	No	No indication	Farquhar-von Caemmerer-berry (fvcb)
	Moriondo et al. (2019)	Yes	No	Yes	No	No	Photosynthesis-light response curve
	Buwalda (1991)	Yes	Yes	Yes	No indication	No indication	No indication
MaluSim	Lakso et al. (1999) and Lordan et al. (2019)	Yes	No	Yes	No	No	Charles-Edwards model
CLM5-Fruit-Tree model	Dombrowski et al. (2022)	Yes	No	Yes	Yes	Yes	No indication
	Bevacqua et al. (2021)	Yes	No indication	Yes	No indication	No indication	Photosynthesis-light response curve

(2021)). In addition, only fruit quantity is represented and fruit quality is never considered.

The model of Moriondo et al. 2019 could be further developed to represent and simulate the functioning of fruit-based agroforestry systems. Indeed, it is the only model that integrates crops under the fruit tree. However, it lacks the representation of important cultural operations such as fertilisation, canopy management, etc. Other models, such as those of Morales et al. 2016 and López-Bernal et al. 2018, can also be developed, by integrating crops under the trees and implementing other fruit management practices.

One strong limitation of compartmental models is the time step of the simulation. Most of the models have a daily time step, which is a compromise between calculation time and simplification. Because of this time step, the effects of some climatic hazards (including frost) are difficult to model. Indeed, the number of hours during which temperature is below a threshold is important to determine frost damage (Rodrigo 2000; Strang et al. 1980). An hourly time step at certain key points of fruit development may be required. In the future, with the development of computer power and the widespread availability of weather data at the hourly time scale, these models could be adapted to take into account hourly weather data at least during the critical phenological stages. Another limitation of these models is that pests *sensu lato* (including diseases) are not taken into account (except one pest for the model of Gutierrez et al. (2009)). The damage caused by the pests can be very consequent and impact in particular fruit production. Induced by many factors, their consideration in the future will not be straightforward.

Diversity of plot-scale models of tree-crop associations

In the literature, various types of agroforestry models have been developed: (i) allometric models, (ii) no growth models of soil carbon, (iii) plot scale models of tree and crop growth, (iv) architectural models, (v) farm decision models, (vi) landscape models (Burgess et al. 2019; Luedeling et al. 2016). To represent the development of an FT-AFS, the model should be able to simulate the development of the tree in three dimensions (spatial heterogeneity of competitions between tree and crops) and take into account different cultural operations. Thus, the most relevant models to reach this goal are the plot scale models of tree and crop growth.

A comprehensive review of agroforestry models presented by Burgess et al. 2019, detailed the three plot scale models: (i) Yield-Safe (Van der Werf et al. 2007 ; Graves et al. 2010), (ii) WaNulCas (Van Noordwijk and Lusiana 1999), (iii) Hi-sAFe (Dupraz et al. 2019) (Table 5). These three agroforestry models are described in Supplementary Information C. Another review of agroforestry models presented by Kraft et al. (2021) mentioned other agroforestry models (Kraft et al. 2021), such as APSIM (Smethurst et al. 2017), SCUAF (Young 1998), EPIC (Easterling et al. 1997), SBELTS (Qi et al. 2001), WIMISIA (Mayus et al. 1999), COMP8 (Smethurst and Comerford 1993), DynACof (Vezy et al. 2020), HyPAR models (Mobbs et al. 1998).

These 11 agroforestry models are compared to each other in Table 6.

In order to simulate the development of an agroforestry system including fruit trees, some models appear less adapted. Each model has its own specificities. The COMP8 model does not consider intercropping but only permanent grassing. The EPIC, Sbelts and Wimisia models are adapted to represent only windbreak agroforestry systems. The DynACof model is adapted to represent coffee-based agroforestry systems. These models seem less adapted to simulate temperate FT-AFS.

Due to its 1-dimensional nature, Yield-SAFE cannot take into account the spatial heterogeneity of competition between tree and crops. But, this model is relevant to test the productivity of agroforestry systems at a larger scale (Palma et al. 2007). The WaNulCas model is limited by its two dimensions, especially at temperate latitudes where the elevation of the sun in the sky is low. Indeed, these two dimensions effectively correspond to the assumption that the interception of light is identical on the west–east side as on the north–south side (Burgess et al. 2019; Hussain et al. 2016). This inaccuracy leads to an error in approximation of light interception and indirectly on photosynthates production. The APSIM model is also limited by its two dimensions. This model does not provide the capability to simulate different species in the same field. The SCUAF model does not consider different crops and tree species. The Hi-sAFe model, in three dimensions, permits reducing this approximation, and offers belowground competition in 3D, which is a key improvement for predicting water and nitrogen uptake by trees and crops.

The Hi-sAFe model seems to be the most appropriate model according to the selected criteria. This model simulates 3-dimensional systems and therefore allows for spatial heterogeneity of competitions between trees and crops to be taken into account. This model, like other agroforestry models, simulates systems over long enough periods (several years) to represent the phenomena of complementarity and competition. Finally, this model integrates some cultural operations such as irrigation, fertilisation, pruning of lower tree-branched and root-pruning. This model does not seem to be able to simulate fruit tree systems yet. The development of this model and the addition of new processes are necessary to simulate FT-AFS. However, other models such as DynaCof seem equally relevant to develop. This model could be adapted by adding mechanisms to represent temperate agroforestry systems.

Discussion: choosing the appropriate model for the simulation of FT-AFS

The choice of the model depends on the simulation objectives

This review shows the diversity of models that have been developed to simulate fruit tree or agroforestry systems. Each model was written for a specific context and towards specific objectives. As a result, models differ in terms of the level of detail in the simulated processes, spatial dimensions, time periods,

Table 5 Summary of the several aspects on the fruit trees non-fine architectural scale models.

Bibliography	Species	Dimension	Spatial scale	Pruning	Irrigation	Fertilisation	Fruit load management	Ressource competition	Fruit quality	Crops species
Grossman and DeJong (1994)	Peach	0d	Field	No indication	No	No	Yes	No indication	No indication	No
Abdel-Razik (1989)	Olive	0d	Field	Yes	Yes	Yes	No indication	No indication	No indication	No
Gutierrez et al. (2009)	Olive	2d	Landscape	No	No	No	No	No	No	No
Viola et al. (2012)	Olive	2d	Field	No	Yes	No indication	No indication	No indication	No indication	No
Maselli et al. (2012)	Olive	2d	Landscape	No	No	No	No	No	No	No
Morales et al. (2016)	Olive	3d	Field	Yes	No	No	No	Yes	No	No
López-Bernal et al. (2018)	Olive	3d	Field	Yes	Yes	No	No	Yes	No	No
Moriondo et al. (2019)	Olive	2d	Field	No	Yes	No	No	No	No	Yes
Buwalda (1991)	Kiwi	0d	Field	No	No	No	No	No	No	No
Lakso et al. (1999) and Lordan et al. (2019)	Apple	0d	Field	No	No	No	No	No	No	No
Dombrowski et al. (2022)	Apple	No indication	Field	Yes	Yes	Yes	No	No	No	No indication
Bevacqua et al. (2021)	Peach	0d	Field	Yes	No indication	No indication	Yes	No indication	No indication	No

Table 6 Summary of the description of the different process-based agroforestry models.

Models	Dimension	Stress	Irrigation	Fertilisation	Forest tree	Fruit tree
Yield-SAFE	1	Water, light	Yes	No	Yes	No
WaNulCas	2	Water, nitrogen, light	Yes	Yes	Yes	No
Hi-sAFe	3	Water, nitrogen, light	Yes	Yes	Yes	No
APSIM	2	Water, nitrogen, light	Yes	Yes	Yes	No
SCUAF		Water, nitrogen, phosphorus		Yes	Yes	Yes
EPIC	2	Water, nitrogen, phosphorus	Yes	Yes	Yes	No
SBELTS	1		Yes	No	Yes	No
WIMISIA	2	Water, light			Yes	No
COMP8	2	Potassium and phosphorus			Yes	No
DynACof	3	Water, nitrogen			Yes	No
HyPAR		Water, nitrogen			Yes	No

or ability to simulate various different agricultural practices.

In order to avoid having to develop from scratch a model for each new scientific question, it should be possible to re-use/adapt existing models. But choosing the right model to start from might not be easy as models differ according to several criteria, such as the species for which they were developed and parameterized, the processes they simulate or the management operations they allow representing. Arguably, the latter two aspects are more important than the first one, because the strength of mechanistic models is their genericity: they constitute important ecophysiological processes that are shared among fruit trees, and only the values of the parameters differ between species. Thus, the choice of a model should rather be based on the level of detail of the processes that they represent and on the type of cultural operations that they allow simulating than on the species for which it was initially developed. In other words, if the initial model is parsimonious in terms of parameters/variables/processes, then it should not be too complicated to adapt to a species that behaves similarly. Another important criterion for the choice of a model is of course that it must be validated against field measurements. Even when it is, adaptation to another tree species will require further validation based on observations of the new species.

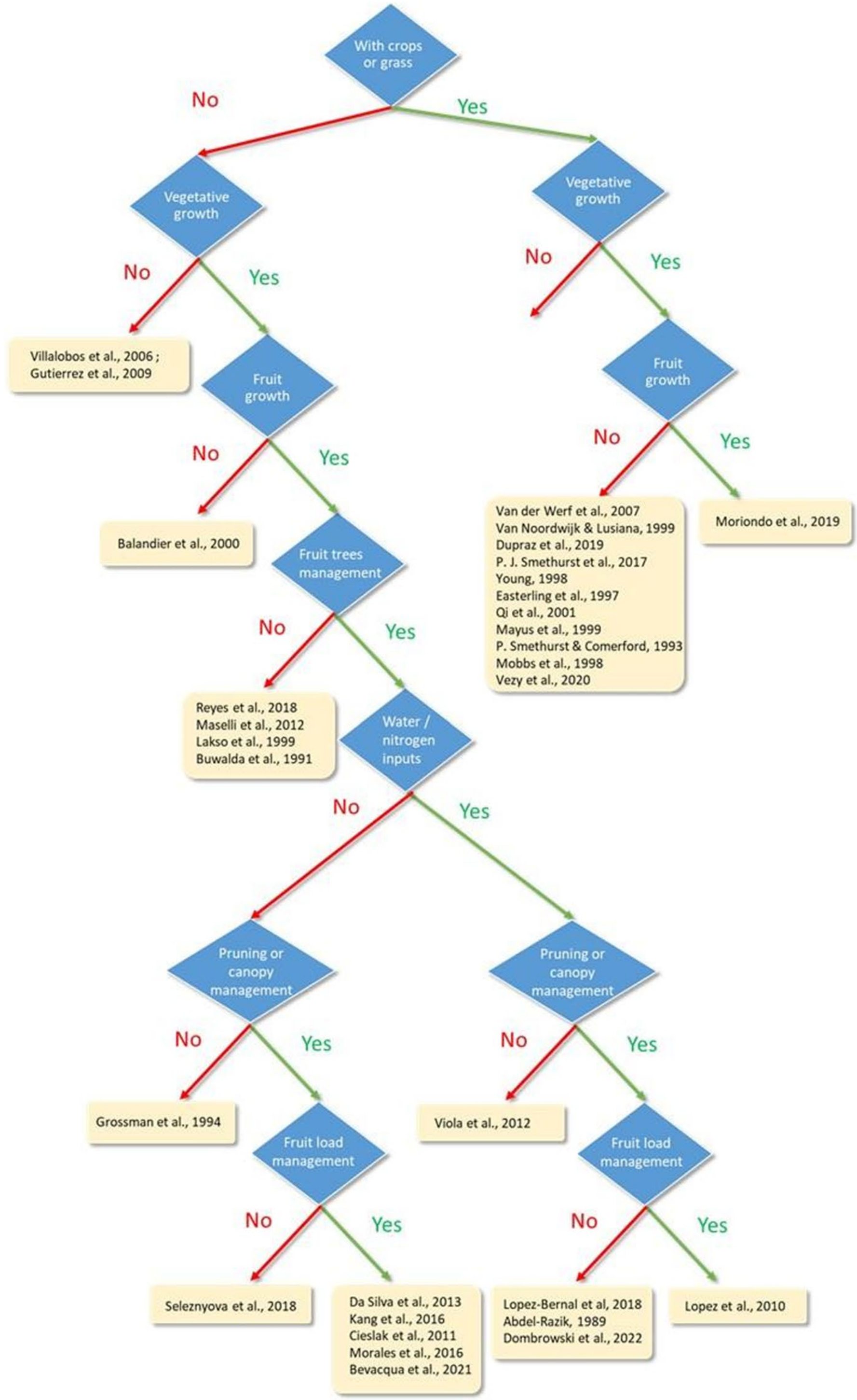
Here, we propose a typology of fruit tree models according to the processes/cultural practices that they can include. This classification can then be used to choose the right model as a function of the level of detail that modellers wish for the model, according to their simulation objectives (Fig. 3). Indeed, an important rule in modelling is to stay as simple as possible, but not simpler, so the classification starts from the simplest model, and goes towards more complexity.

No existing model is able to simulate FT-AFS, but some could be improved to reach this goal

None of the reviewed models can integrate all processes to simulate agroforestry systems based on temperate fruit tree, i.e. simulate both the interactions (competition for light, water, nutrients, facilitation through buffered microclimate or increased infiltration) between trees and crops in space and time, and the development and growth of fruits and associated management. Based on the three criteria we defined (i) space in 3D to represent tree-crop interactions, (ii) time with a sufficiently long time period, (iii) cultural operations (considering the four most important: irrigation, fertilisation, fruit load management, pruning) taken into account, two models appear almost suitable:

- the model of Moriondo et al. (2019) partially validates two criteria. This model allows simulation of the development of an orchard associated with different crops over several years. However, the model represents this interaction in 2D only and does not consider the heterogeneity of shading on crops or grass. For the cultural operations, only irrigation is considered. The model does not integrate fertilisation, tree pruning or fruit load management.

Figure 3 Choosing a fruit tree model according to the user's needs in terms of elements of the cropping system to represent. Twenty models classified according to the simulation of: (i) biotic interactions with crops or grass, (ii) vegetative growth, (iii) fruit development, (iv) fruit development, (v) fruit tree management, (vi) irrigation and/or fertilisation, (vii) pruning or canopy management, (viii) fruit load management.



- the Hi-sAFe model, meets completely two of the three criteria: 3D representation of space, simulation of tree growth over several years at a daily time scale, and simulates all cultural operations of the crop and some of the tree management operations. However, this model lacks the representation of the fruits and associated practices.

These two models could be enhanced by adding the missing features. For example, work is currently under progress to improve the Hi-sAFe model by adding a tree fruit compartment and the related processes (fruit setting, carbon allocation to fruits) and cultural operations (fruit load management), and by adding more types of pruning, required for the management of fruit trees (canopy trimming, canopy topping, canopy thinning). This literature review was conducted only on models elaborated on temperate species. But, other models on tropical fruit tree species exist, such as V-Mango (Boudon et al. 2020) or physiological models of coffee (Van Oijen et al. 2009), and could partly fulfil the three criteria or at least provide some formalisms that could be revalorized.

Other desirable features for future FT-AFS models

The vast majority of models were parameterized only for an archetypal individual of a given species and do not examine the intra-specific variability. However, due to human selection of diverse cultivars for various cropping situations and final use, the intra-specific variability in tree size, shape, fruit load, fruit size, etc. is huge. Parameterization of all the parameters on the selected cultivar would increase the reliability of the simulations (but would of course come at the price of having to measure all parameters in all cultivars). A more reasonable alternative would be to identify which parameters are most cultivar-dependent, and measure only these parameters for each cultivar, the other parameters being fixed for a given species. These cultivar-dependent parameters could be parameters linked to the adaptation to local climates (e.g. phenological parameters) or to specific commercialisation requirements (e.g. parameters driving fruit size and quality).

Indeed, fruit quality is an important aspect for fruit growers, which is often overlooked by fruit tree models (among the 21 fruit trees models described here, only the Qualitree model (Lescourret et al. 2011) considers yield quality through the concentration of certain sugars in the fruit). Other variables concerning yield quality could be taken into account in fruit tree models such as oil content (e.g. for olive trees), concentration of certain molecules, fruit firmness, etc. (Saldaña et al. 2013).

In these models, none of them consider all pests and crop auxiliaries. Some incorporate only one pest, such as the model of Gutierrez et al by taking into account the olive fly effect. These models can still evolve to incorporate biotic components, such as pests and crop auxiliaries.

Conclusion and perspectives

Fruit tree based agroforestry systems are attractive to farmers, as the fruits of the trees provide rapidly, in a few years, an annual income, while timber tree based agroforestry systems do not provide any revenue from the tree in the short or medium term. This may explain why FT-AFS are currently more attractive and adopted by European or North American farmers than timber tree based systems (Lauri et al, 2016). But these systems have not been intensively researched nor practised, and virtual experiments are likely to help more accurately design fruit tree-based agroforestry models.

In this review, no existing model has been identified to simulate the development of a temperate FT-AFS. The literature search focused on temperate fruit trees and agroforestry models and identified 32 models with very different objectives. None of the fruit tree models meets the three criteria that we deemed most important to simulate FT-AFS [(i) 3D growth, (ii) long time period, (iii) management practises). However, the model of Moriondo et al. (2019) partially meets the criteria of modelling both fruit tree and crop growth, with a simulation time over several years]. Similarly, none of the agroforestry models meets the three stated criteria. However, the Hi-sAFe model partially meets the criteria (fruit trees and crops growth in 3D, simulation over the life of the system, some management practices operations). In order to meet the specified criteria, these two models could be adapted by adding several processes and re-calibrating/validating the models using independent datasets. This review also provides model users with a decision support tree to guide the user to the model that meets their simulation objectives.

Models able to simulate FT-AFS could then be used to predict the system yields and ecosystem services in different pedoclimatic conditions. These models could also be used to optimise the dynamic spatial arrangements, by testing different tree density, tree-crop distances, crop rotation. By using predicted future climatic conditions, the model can also be used to explore the resilience to climate change of FT-AFS. Implementation of FT-AFS optimisation thanks to models will foster a more resilient and more sustainable horticultural production.

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Declarations

Conflict of interest The authors declare no competing interests.

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