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Parametrization of an agroforestry model: from forest trees to olive trees

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Abstract

The conventional cultivation of olive trees can lead to environmental degradations such as soil erosion and loss of biodiversity. Agroforestry systems could bring solutions to these environmental degradations. A simulation model able to represent the growth and interactions between olive trees and annual crops would be useful to rapidly test and evaluate innovative olive-based agroforestry systems without the need for space and time-consuming field experiments. The Hi-sAFe model simulates agroforestry systems in three dimensions according to interactions between forest trees and annual crops for water, nitrogen and light. However, this model was developed and parameterised only for forest trees and not for fruit trees whose balance between the vegetative and the fruit organs is crucial. Two main adaptations were made to the model to simulate olive-based agroforestry systems: the addition of a fruit-setting module and the carbon allocation module adaptation. Here, we present the experimental estimation of two important parameters of these modules, both at tree scale: the maximum number of fruits m^{-2} leaf area and the maximum daily carbon allocation to fruits. The maximum fruit load per olive trees was estimated at 1356 fruits per m^2 leaf area using three genotypes of an 'Arbequina' \times 'Oliviere' progeny. To determine the maximum daily carbon allocation to fruits, we hypothesized a cultivar effect. For these reason, nine olive trees, of three cultivars ('Leccino', 'Cypressino' and 'Manzanille'), with a low fruit load were selected from the three cultivars, and samples of fruits were dry-weighted every week for 12 weeks during fruit growth. The maximum daily carbon allocation to fruits ($\text{g carbon olive}^{-1} \text{ day}^{-1}$) varied significantly between 'Leccino' and 'Cypressino' (3.9×10^{-3} and 4.3×10^{-3} , respectively) and 'Manzanille' (7.3×10^{-3}). The value of these two parameters not identifiable in the literature can be set to 1356 fruits m^{-2} of leaf area (maximum number of fruits m^{-2} leaf area) and at $7.3 \times 10^{-3} \text{ g carbon olive}^{-1} \text{ day}^{-1}$ (maximum daily carbon allocation to fruits).

Keywords: innovative systems, Hi-sAFe model, carbon allocation, leaf area, fruit, agroforestry

INTRODUCTION

In the case of olive tree, *Olea europaea* L., three main cropping systems dominate: traditional or extensive (140 trees ha^{-1}), semi-intensive (up to 400 trees ha^{-1}) and intensive (up to 2500 trees ha^{-1}) (Loumou and Giourga, 2003; Russo et al., 2016). These systems can, in some cases, lead to environmental impacts including soil erosion and loss of biodiversity (Gómez et al., 2009; Milgroom et al., 2007). One of the solutions to environmental degradation and loss of diversity may be biodiversified systems, such as agroforestry systems.

Agroforestry systems are defined as a set of agricultural practices that combine trees with crops and/or livestock. These systems can maximise production per land unit area, increasing the total yield of the system (tree and crop products) by up to 30% compared to the rotation of agricultural plots on one side and the reforestation of an agricultural plot on the other (Dupraz and Liagre, 2011). In these systems, trees are mostly of forest origin, like walnut and poplar trees. Fruit trees are currently seen as a strongly added value to agroforestry and in these systems, the main crop is often the fruit tree instead of forest trees (Pantera et al., 2018). Indeed, 11% of the total European agroforestry area is composed of

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fruit trees especially olive and apple trees (Lauri et al., 2019).

To test and evaluate different agroforestry systems, the dynamic-3D and mechanistic model Hi-sAFe has been developed. The model is based on two assumptions: i) the productivity of agroforestry systems depends on the acquisition of heterogeneous resources by trees and crops in the environment, and ii) the interaction between trees and crops is governed by the aerial, subterranean and phenological plasticity of plants. The Hi-sAFe model is able to simulate agroforestry systems according to interactions between trees and crops for water, nitrogen and light. Simulations are performed over the entire life of the system: from planting to tree harvest (Dupraz et al., 2018, 2019; Reyes et al., 2021). Currently, this model is parameterised only for three tree species: poplars, hybrid walnuts and wild cherry. The Hi-sAFe model is not adapted to simulate fruit trees like olive trees and no relevant model has been found in the literature to simulate agroforestry systems including fruit trees. To adapt the Hi-sAFe model to fruit trees, several formalisms have been added to it to simulate the growth and yield of olive trees: a phenological scale describing fruit phenology, a modification of leaf senescence allowing evergreen foliage, a balance between the fruit and vegetative compartments and carbon allocation to the fruit compartment.

In the literature, some values are available for parametrisation, but experimental design and/or measurement units are not always detailed. Consequently, experiments were conducted in 2021 at INRAE in Mauguio to found the required values for the model parametrization.

In this article, we will focus on some basic architectural parameters that are necessary to represent fruit trees and we will discuss the parameterisation of maximal fruit number m^{-2} leaf area and maximum daily carbon allocation per fruit.

MATERIALS AND METHODS

New formalisms added to Hi-sAFe to incorporate fruits

Hi-sAFe model is composed of several input variables: i) weather, ii) soil description, iii) crop description, iv) tree description, v) tree and crop technical itinerary description. For tree description, 127 parameters were required and separated on different modules (Table 1). Some parameters were specific to fruit trees and the other were parameterized and calibrated for olive trees.

Table 1. Summary of number of parameters per module within Hi-sAFe model.

Tree module parameters	Number of parameters	Parameterized (P), calibrated (C), measured (M)	Generic formalisms or fruit tree formalisms
Generic	3	P + M	Generic
Phenology	11	P	Generic
Light	12	P + C	Generic
Microclimate	4	P + C	Generic
C allocation	34	P + C + M	Generic
Roots	13	P + C	Generic
Water repartition	7	P + C	Generic
Fruit compartment	27	P + C + M	Fruit tree

Each day, a daily amount of carbon is assimilated by the tree. Depending on the phenological stage, the carbon can be allocated to the labile carbon compartment (i.e. the carbon reserve) or to growth (Figure 1).

The carbon allocated to growth is distributed according to the above-ground and below-ground carbon equilibrium. The carbon allocated to the aerial compartments is distributed to four compartments: leaves, branches, stump and stem. In addition, a fruit module is implemented to simulate fruit trees, including the fruit carbon compartment. The fruit carbon allocation module is based on two formalisms (Figure 1): 1) the number of fruits and flowers, 2) the carbon partitioning to fruits and flowers. This module is initialised by a variable: the

initial net number of flowers. This variable is calculated according to the leaf area (maximal fruit number m^{-2} leaf area) and the labile carbon reserves of the tree. At the time of flowering, this number of initial flowers decreases with both heat (Koubouris et al., 2009) and cold stresses (Barranco et al., 2005). This number can also be reduced by a cultural practice, called fruit thinning. At the time of flowering, the number of initial flowers is divided by the duration of flowering. Consequently, a daily number of flowers appears at the time of flowering (number of flowers days^{-1}). For the carbon allocation to the flower and fruit compartment, a carbon sink is calculated. The latter is computed as a function of a carbon allocation parameter to the fruit compartment and as a function of the maximum daily carbon allocation per fruit. According to Villalobos et al. (2006), 50% of the carbon allocation to the aerial compartment is allocated to the fruit compartment in a fruitful olive tree. The fruit compartment becomes the priority for carbon allocation. Therefore, two carbon sink variables are calculated: i) the daily carbon available to fruit based on the coefficient of Villalobos et al. (2006), and ii) the maximum daily fruit growth. The minimum value of these two sinks corresponds to the carbon allocated to the fruit compartment.

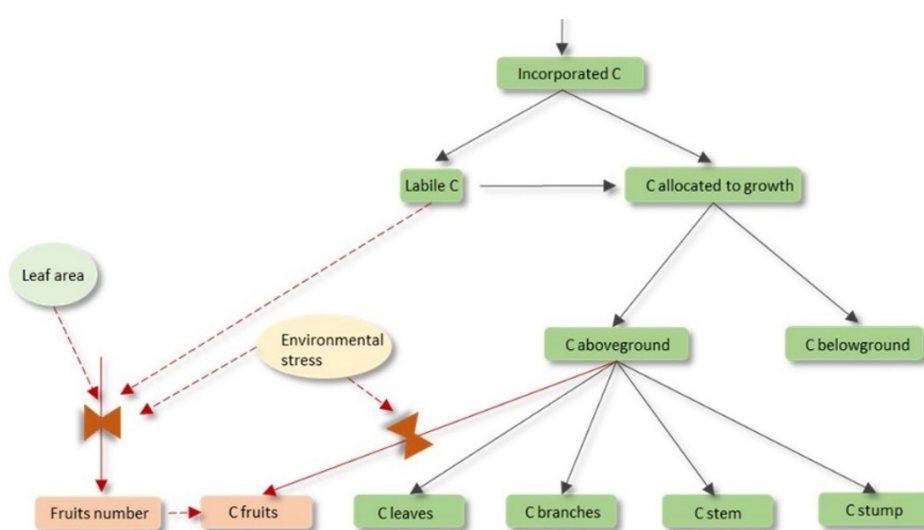


Figure 1. Conceptual scheme of carbon (C) allocation module in the Hi-sAFé model.

In this fruit compartment, two most important parameters must be measured to parameterize this model: the maximal fruit number m^{-2} of leaf area and the maximal daily fruit growth.

Parameterisation of the fruit carbon allocation

Two experiments were conducted to parametrise the model. The first experiment was carried out in an 19 year old olive grove at INRAE's experimental domain in Mauguio, in the South of France, in 2021. The goal of this experiment was to identify the maximal fruit number m^{-2} leaf area and to estimate the maximal quantity of fruit carbon allocation m^{-2} leaf area. This experiment was carried out on three genotypes with a high fruit load (estimated the maximal number of fruits m^{-2} of leaf area) issued from a progeny ('Arbequina' × 'Oliviere'). For each genotype, eight production units (i.e. the part of the branch bearing fruits, Figure 2; Chol et al., 2011) were identified in bottom and top positions within the tree. To test, the position effect in the number of leaves in the olive tree (top or bottom position), a multiple linear model (leave ~circumference + position) was used.

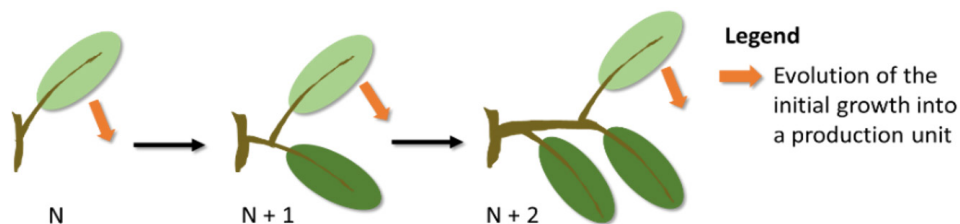


Figure 2. Distinction and evolution over time of initial growth (clear green) to production units (dark green) in the olive tree.

In this experiment, some variables were measured: number of fruits tree⁻¹, dry matter of 100 fruits, circumference of all branches, sample of individual leaf area (estimated by Winfolia® software), number of leaves on selected branches. Other variables were estimated including the number of fruits m⁻² leaf area and the maximal quantity of fruits carbon allocation m⁻² leaf area (Figure 3).

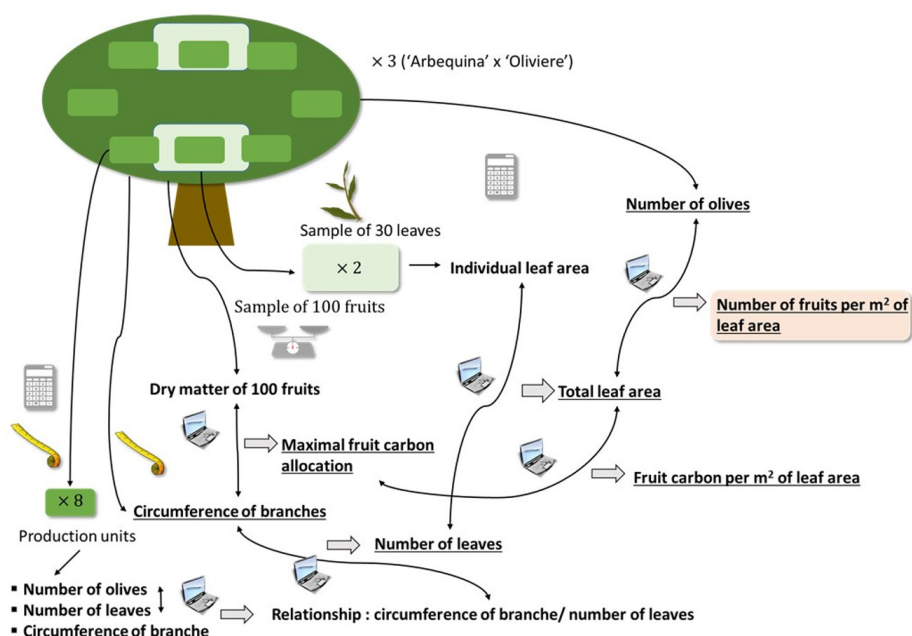


Figure 3. Protocol of the experiment to determine the number of fruits m⁻² of leaf area. To determine leaf area, Winfolia® software was used. The underlined variables are those calculated at the tree level, the others are calculated at the leaf production unit level.

The second experiment was carried out in another olive grove of the same experimental domain in Mauguio (France), in 2021. The goal of this experiment was to identify the maximum carbon allocation per fruit and per day, and to identify the dynamic of carbon allocation to fruits. This experiment was carried out in three cultivars: 'Leccino', 'Cypressino' and 'Manzanille'. For each cultivar, three olive trees with a low fruit load (to avoid fruit to fruit competition) were selected by expert opinion. Every week after fruit setting, 10 olives tree⁻¹ were harvested. These olives were weighed to record their fresh weight (FW). The olives were placed into an oven at 70°C until a constant dry mass was reached. The olive dry mass was converted into olive carbon quantity by a constant ratio 0.42 (Brisson et al., 2009). The dynamics of carbon content as a function of time since flowering was approximated with a linear relationship with an intercept at 0.

Statistical analyses

For the first experiment, a linear model was used to test the relation between number of leaves and circumference (with a significance level of 5%) as a function of leaves position: circumference and intercept. To determine the effect of genotype on leaf area, a Kruskal-Wallis test was used. For the second experiment, ANOVA was used to test the effect of tree cultivar on the slope of olive dry matter against time.

RESULTS AND DISCUSSION

Maximal fruit number m⁻² leaf area

The single leaf area of the production units of three olive trees varied from 2.74 to 3.72 cm². The correlation between the circumference and the number of leaves was positive (p-value <0.001; Figure 4).

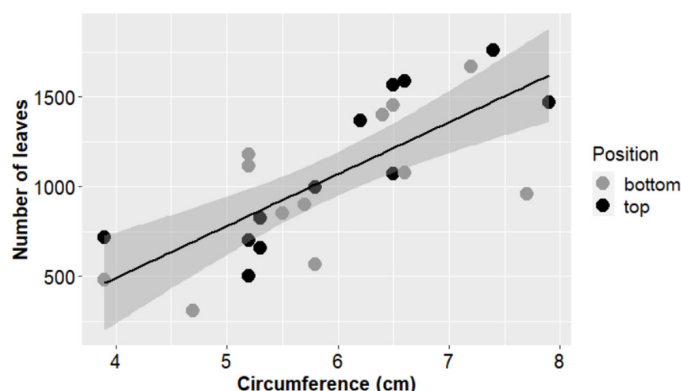


Figure 4. Linear relation between the circumferences of the production units (see Figure 1) and their number of leaves for three trees of a progeny of ‘Arbequina’ × ‘Oliviere’. Each value represents a production unit tree⁻¹ at different positions within the trees (bottom in gray color and top in black color). No significant differences between position in tree canopy were observed (multiple linear model (leaves ~circumference + position), p-value=0.55) and a unique equation was generated. Linear equation: $Y = -663.79 + 288.98x$ (p-value <0.001).

Based on this relationship, the leaf area tree⁻¹ was computed for the three collected trees (Table 2).

Table 2. Main variables calculated to estimate the maximal fruit number m⁻² of leaf area in a progeny (‘Arbequina’ × ‘Oliviere’). Significant differences in leaf area according to genotype (olive tree number) (Kruskal-Wallis test, p-value=2.33×10⁻⁵).

Olive tree code	Number of leaves	Average leaf area of one leaf (cm ²)	Total leaf area (m ²)	Number of olives	Dry matter (g for 100 fruits)	Fruits m ⁻² leaf area (fruits m ⁻²)	Fruit carbon m ⁻² leaf area (g C m ⁻²)
G8	55021	2.74	15.07	19906	51.47	1356	293.25
J17	27012	3.72	10.04	6826	69.83	706	207.01
K43	70835	3.24	22.93	26240	60.50	1172	297.86

The three olive trees, although with a same fruit-load based on a visual expertise, were heterogeneous in terms of number of leaves, total leaf area and number of fruits. Leaf area and number of olives tree⁻¹ could vary by a factor of two and four, respectively. The quantity of fruit carbon m⁻² leaf area vary by a factor of less than two. It is likely that these numbers of

olives kg^{-1} were related to a high load if we compare to results of the number of olives kg^{-1} of medium load trees that vary between 188 at 356 fruits ('Gemlik') (Uylaser et al., 2008).

The maximal fruit m^{-2} of leaf area, allow initiating the number of fruits tree^{-1} and this parameter was parameterised at 1356 fruits m^{-2} leaf area (G8 genotype).

To illustrate, the maximal fruit number m^{-2} leaf area parameter is very important parameters, and allows to estimating the fruits tree^{-1} (Figure 5).

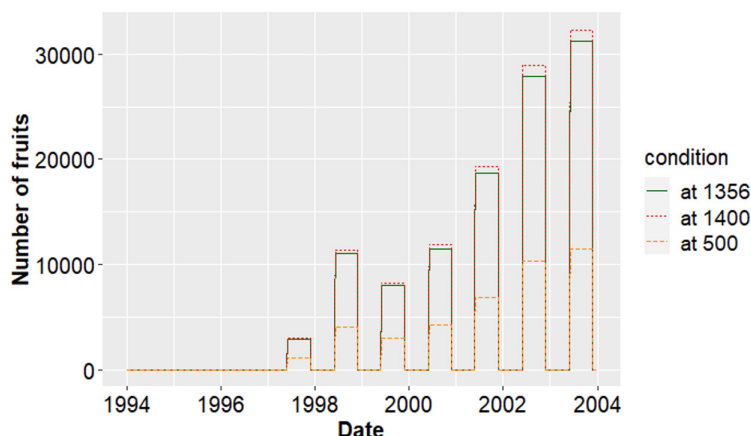


Figure 5. Modeling results: fruits number of olive tree in comparison with different values for the maximal fruit number m^{-2} leaf area parameter.

Maximum daily carbon allocation per fruit

The fruit dry mass increased with time. The 'Manzanille' cultivar had larger fruit dry weight, with 13.77 g fruit^{-1} , in comparison with fruits of the other two cultivars, with 9.3 and 10.09 g for 'Leccino' and 'Cypressino' cultivars, respectively (Figure 6). These values are similar to the ones obtained by Giuffrè (2017) on 'Leccino' and by Hartmann (1948) on 'Manzanille', although in this latter case no clear indication of fruit load is given.

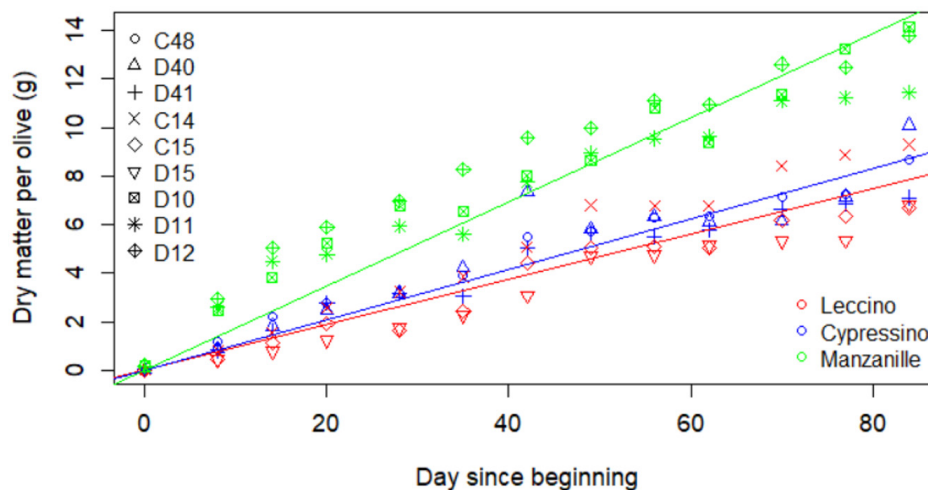


Figure 6. Seasonal pattern of dry matter in olives of three cultivars ('Leccino', 'Manzanille' and 'Cypressino'). Each point is a single value measured on a batch 10 olives tree^{-1} . Significant effect of cultivar on the slope of olive dry matter against time (ANOVA, $p\text{-value}=3.90 \times 10^{-5}$).

The maximum carbon allocation value varied between each cultivar. The maximum

carbon allocation per fruit and per day was calculated at 3.92×10^{-3} , 4.36×10^{-3} and 7.29×10^{-3} g carbon/olive/day for 'Leccino', 'Cypressino' and 'Manzanille' cultivar, respectively.

This parameter can thus be considered as a varietal parameter. 'Leccino' and 'Cypressino' were very similar, but a difference exists for 'Manzanille'. However, this experiment was carried out only in one year and one geographical location. To confirm these values further experiments should be carried out.

CONCLUSIONS AND PERSPECTIVES

To adapt this model to olive trees, a number of formalisms have been added and the ranges of the parameters were identified. Experiments were carried out on olive trees to determine two parameters: the maximal fruit number m^{-2} leaf area and the maximal daily carbon allocation per fruit. The values obtained for these parameters were estimated at 1356 for the maximal fruit number m^{-2} leaf area parameter and 7.29×10^{-3} for the maximal daily carbon allocation per fruit parameter.

This model could also be used to further analyze the productivity of agroforestry systems. For example, a recent article analyzed wheat yield obtained on an almond/wheat agroforestry system (Zhang et al., 2022). Although wheat yield is impacted by the shape and position of the trees, we consider that canopy porosity, not taken into account in Zhang et al., (2022) study, should also be considered. In the Hi-sAFé model, fruit tree pruning decreasing leaf density could be used to identify optimal canopy porosity to increase the yield of the agroforestry system.

In perspectives, once parameterized and calibrated, the Hi-sAFé model will be used to test and evaluate different agroforestry systems based on olive trees. Co-design workshops are currently organized with different stakeholders (olive growers, agricultural advisors, researchers) with the objective to design innovative systems. These systems co-constructed will be tested and evaluated according to different agronomic outputs (fruit yield, fruit weight, oil content) and different environmental outputs (water runoff, nitrogen leaching, water infiltration, nitrogen mineralization). Their sustainability will also be evaluated using IPCC (Intergovernmental Panel on Climate Change) climate projections.

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