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How to reconcile short-term and long-term objectives in mixed farms? A dynamic model application to mixed fruit tree - vegetable systems

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Abstract

Mixed fruit tree and vegetable (MFV) farms correspond to the joint production of fruit trees and vegetable crops. In temperate regions, this emerging farming system is a potentially attractive land use to foster the diversification of agricultural systems. However, these systems combine two productive and labor-intensive enterprises (orchard and market gardening) and in practice, the system feasibility depends on the availability and need for labor. Long-term yield predictions are needed to assess the economic profitability of such innovative farming systems. A dynamic bio-economic model of MFV systems was developed to assess its main properties over time. This simple state-control model is based on yields, biological dynamics, workload requirements and economic profitability of each farming enterprise. Due to the lack of data from long-term experiments, the model was parametrized on data from specialized systems and calibrated with expert knowledge. The implementation of the model made it possible to simulate management strategies for vegetable crops and fruit trees, and to assess their impact on the long-term system dynamics. Results show that specialized market gardening enterprise has an overall higher profitability per hectare than specialized fruit trees. Nevertheless, mixed systems composed of roughly equivalent shares of fruit trees and vegetable crops make it possible to decrease workload constraints while maintaining a high level of profitability. In

addition, intermediate shares of fruit trees and vegetable crops can lead to higher profitability in the long term, but require addressing both short- and long-term objectives, and the ability for farmers to cope with several consecutive years of lower income. Further research is now needed to better understand the biological processes underlying MFV systems and their evolution in different management configurations.

Keywords: crop diversification; horticulture; mixed horticultural farms; dynamic modeling

1. Introduction

The productive and environmental challenges that agriculture is facing have led to the emergence of new farming models based on agro-ecological paradigms (Altieri, 2004; Wezel et al., 2014). These models are built on a high agrobiodiversity, combining cultivated and natural elements within the agroecosystem. One of these, known as Mixed Fruit tree-Vegetable system (MFV), which corresponds to the joint production of fruit trees and vegetables is attracting a growing interest in Europe, especially among new farmers (Léger et al., 2019; Warlop, 2016). In addition to being highly diversified (up to 20-30 crop species), these systems combine two productive and highly labor-intensive enterprises: orchard and market gardening. This represents a diversification strategy that goes further than increasing the number of crops, since it adds a *functional* diversity provided by fruit trees. These farming systems, which were still extremely rare at the beginning of this century, are currently undergoing a strong development, in line with the current trend of the establishment of small organic farms, generally created by people without any previous family farming ties (Léger et al., 2018).

The existing literature on MFV deals mainly with their conception (Sieffert et al., 2014; Warlop and Castel, 2016), or consists of detailed descriptive analyses (Léger et al., 2018; Pantera et al., 2018). While this work is important, it leaves farmers somewhat lacking regarding the management of these systems, as the interactions between agro-ecological processes and management actions are not taken into account. However, the management of MFV is particularly challenging for two main reasons. The first reason is linked to the great complexity of these systems, since they add up the intrinsic difficulties of two very demanding systems – orchard and market gardening – to which are added the difficulties linked to the

interaction between these two systems. It involves, even more than for specialized production systems, a need for prioritization between objectives and trade-offs between constraints (Navarrete et al., 2014). The second limitation is related to the differences in temporal dynamics between crop types within such systems combining perennials and annuals.

The simultaneous management of short-term market gardening and long-term orchards, with their own dynamics, can be very complex and jeopardize the long-term viability of the farm. Following van der Werf et al. (2007) we argue that one of the key factors in the success of mixed systems, compared to specialized ones, is the appropriate use of operational resources and more specifically of labor. In practice, trade-offs between short term and long-term objectives imply that farmers have to make compromises in the allocation of working time to each enterprise. Thus, each enterprise may end up being managed in sub-optimal conditions depending on working time needs and supply.

Being able to study various scenarios of resource use, especially labor, and characterizing their consequences on the system properties is therefore paramount. In the specific case of the MFV, since the adoption dynamic is relatively recent, empirical data on mature systems are still very scarce and the modelling approach can overcome constraints of data availability. The existing literature on dynamic models of mixed tree-crop systems focuses mainly on process-based models, like tree-soil-crop interactions (Dupraz et al., 2019, 2005; van Noordwijk and Lusiana, 1999). Some models that integrate socio-economic components mainly deal with timber-based systems (Graves et al., 2011, 2007) and do not consider perennials with annual production such as fruit trees.

In the present study, we built a simple dynamic model of a mixed fruit tree-vegetable farming system making it possible to assess its main properties through time. This model is then implemented to explore different management strategies in MFV farming systems. The ultimate goal of our model is to dynamically predict the long-term evolution of an MFV system under conflicting workload conditions between fruit tree and vegetable enterprises. Running the model under different configurations and settings allows addressing the following questions:

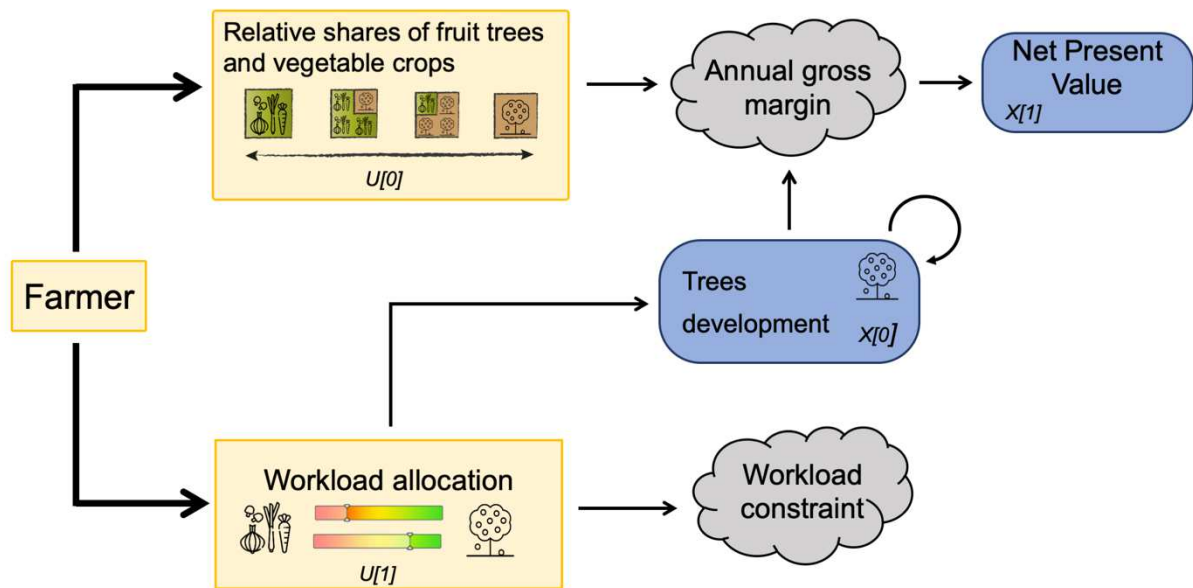
- How do farmers' choices on crop rotation and allocation of their working time impact the system dynamics in the long term?
- How can farmers make the most of the complementarities in terms of working time in an MFV system?
- How can short- and long-term profitability objectives be reconciled in MFV systems management?

90

91 2. Materials and methods

92 2.1. Qualitative description of the model

93 To address our study objectives, we define a discrete time state-control model of a
94 mixed orchard-market gardening system at the scale of a one-hectare farm. The model (Fig. 1)
95 aimed to represent the main biological dynamics while being simple enough to remain
96 understandable. It is based on two sub-models: market gardening and orchard models that are
97 described in the following sections (§2.3 and §2.4). It runs at a yearly time step over a period of
98 20 years. We analyze the dynamics of the states of fruit trees ($X[0]$) and the net present value,
99 which is the discounted cumulative annual gross margin ($X[1]$). The dynamics are steered by
100 two control variables: (i) the crop rotation ($U[0]$) which represents the choice of tree species
101 and vegetable crops grown each year; (ii) the workload allocation ($U[1]$) which refers to the
102 farmer's prioritization of labor between orchard and market gardening.



103

104 **Fig. 1.** Conceptual representation of the model of joint fruit tree – vegetable systems. Blue
105 round boxes stand for the state variables, yellow boxes stand for the control variables and cloud
106 shapes stand for the performance indicators.

108 **2.2. A bio-economic analysis**

109 A variety of conceptual models of mixed tree and crop farming systems economics
 110 have been developed depending on specific contexts and analysis objectives (Luedeling et al.,
 111 2016). When comparing perennial and arable systems, while the economic results of vegetables
 112 occur on an annual basis, timber revenues from trees generally occur once, many years after
 113 system establishment (Graves et al., 2007). The profitability of such mixed systems relative to
 114 pure arable agriculture and forestry can be determined by comparing their net present value
 115 (NPV), calculated from cost–benefit analysis by discounting future benefits and costs (Graves
 116 et al., 2011, 2005; van der Werf et al., 2007). We thus developed a bio-economic model, at a
 117 one-hectare scale, of mixed fruit tree-vegetable systems. The economic value of each enterprise
 118 was calculated using the annual gross margin (GM) calculated as the revenue (R) minus
 119 production costs (including supply costs, labor, machinery) associated with the enterprise (C),
 120 Eq. (1). The fixed costs of structures are therefore not taken into account.

$$\text{Annual Gross Margin} = R - C \quad (1)$$

121 Economic data was retrieved from the Regional Chamber of Agriculture of Provence-
 122 Alpes-Côte d'Azur region. All detailed data for the model are available in Appendix A.

123

124 **2.3. Market gardening sub-model**

125 The market gardening sub-model consists of an intra-annual rotation of vegetable
 126 crops, where each crop represents an equivalent $1/N_v$, N_v being the total number of crops. Each
 127 vegetable crop is defined by a gross margin (VGM) and a workload requirement (WR).
 128 Depending on the workload allocation control ($U[1]$), workload requirement for vegetable
 129 crops may or may not be fulfilled. The amount of working time dedicated to vegetables (W_v) is
 130 therefore the ratio between crop workload requirements (WR_v) and the time actually allocated
 131 (WL_v):

$$W_v = \frac{WL_v}{WR_v} \quad (2)$$

Ultimately, the annual gross margin for vegetables $MG(t)$ depends on the theoretical vegetable gross margin $VGM(t)$ multiplied by the workload actually available for vegetable crops (Eq. (3)).

$$MG(t) = \frac{1}{N_v} \sum_{v=1}^{N_v} VGM_v W_v(t) \quad (3)$$

Note at this stage that the gross margin equations (Eqs. 3 above and 4 below) contain the assumption that yields are proportional to the percentage of required workload expended on the crop. In order to select contrasting market gardening strategies, we simulated all possible combinations of 5 vegetable crops. Based on these simulations, we chose three contrasting management strategies: (1) a low labor-intensive and low-paying strategy; (2) an intermediate labor-intensive and paying strategy; (3) highly labor-intensive, high-paying strategy. These crop rotations are labelled A, B and C respectively in Fig. 2a. On this preliminary result, it is interesting to note that the two Pareto fronts intersect: $A(a) > A(b)$ but $C(a) < C(b)$. Increasing profitability in fruit growing is less time-consuming than increasing profitability in market gardening.

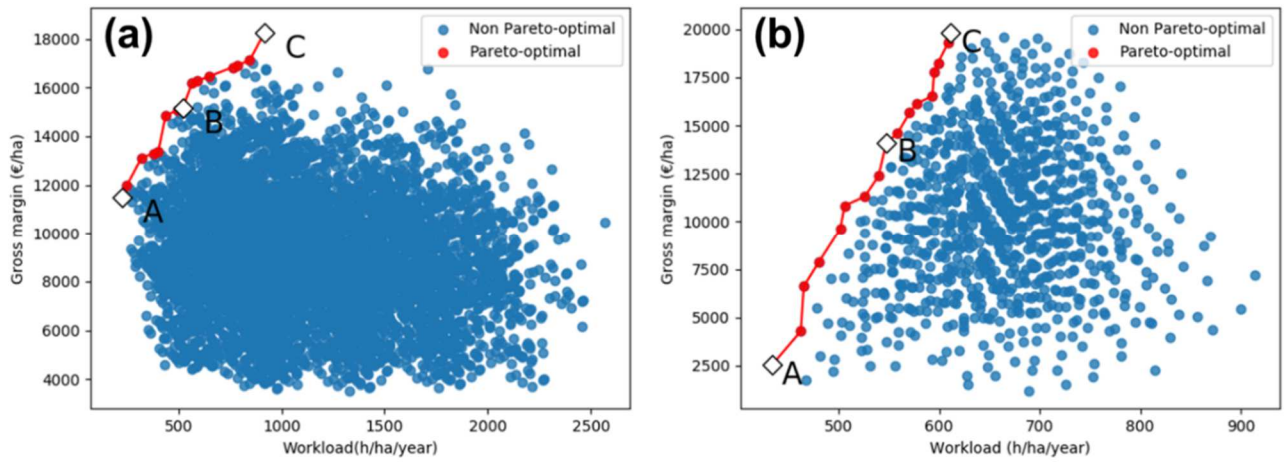


Fig. 2. Gross margin as a function of workload for all possible portfolios of (a) 5 vegetable crops and (b) at least 3 fruit tree species.

2.4. Orchard sub-model

The orchard sub-model is more complex because, due to the perennial nature of fruit species, it is essential to take into account their inter-annual dynamics. We are not aware of any

research that has explored fruit tree dynamics growing in sub-optimal conditions. We therefore used data from pure crop systems, which we calibrated according to experts' knowledge to express their dynamics with a suboptimal management. The orchard sub-model was calibrated in a three-hour collective workshop in February 2020, bringing together 10 fruit tree experts (7 fruit tree technicians and 3 researchers). The production dynamics of each fruit tree species were characterized according to three scenarios: (i) optimal investment, corresponding to the systematic prioritization of trees in the system management, so that they develop optimally; (ii) minimal investment, where only essential operations such as irrigation and training are carried out; (iii) the intermediate scenario stands for an in between situation where tree operations are not done perfectly or are staggered in time. These three scenarios differ in the amount of labour time that the farmer can allocate to the fruit-growing enterprise. This made it possible to characterize fruit tree growth as a function of workload allocation. Some experts were also consulted individually afterwards to refine estimates.

The resulting fruit tree dynamics were fitted using the Nonlinear Least Squares method (Bates and Watts, 1988). Note that the fitted curve has been assumed to have a sigmoidal shape (detailed in Appendix B). Similar to vegetables, the annual gross margin of trees $FT(t)$ was modeled as:

$$FT(t) = \frac{1}{N_f} \sum_{f=1}^{N_f} FGM(t) W_f(t) \alpha(t) \quad (4)$$

where N_f is the total number of fruit tree species in the rotation, $FGM(t)$ is the gross margin of fruit trees, W_f is the workload allocation dedicated to fruit trees and $\alpha(t)$ is the annual tree development coefficient.

As for vegetable crops, we simulated all possible combinations of at least three fruit tree species and we chose three different management strategies (labelled A, B and C respectively in Fig. 2b): (1) a strategy with low labor-demand and low-payoff; (2) an intermediate labor-intensive and payoff strategy; (3) highly labor-intensive, high-payoff strategy.

2.5. Performance indicators and simulations

Several indicators were computed for system performance: the annual gross margin (AGM), the Net Present Value (NPV) and a workload constraint indicator. The annual gross margin (€/ha per year) restates the system profitability into an annual basis (Eq. 5). It was calculated as the sum of the total gross margin from orchard (FT) and market gardening (MG). The AGM allows calculating an inter-annual average and standard deviation of gross margin, which will be used in the study of the dynamics of the system profitability.

$$AGM(t) = FT(t) + MG(t) \quad (5)$$

The net present value (NPV, in € ha⁻¹) of each enterprise was then defined using Eq. (6), as the sum of annual gross margin AGM(t) over a period of T years, discounted by the discount rate (r). The analysis was performed with a 4% discount rate.

$$NPV = \sum_{t=0}^{t=T} \frac{AGM(t)}{(1+r)^t} \quad (6)$$

The last indicator was workload constraint, which was expressed as the yearly relative workload in excess of the workload required by both orchard and market gardening enterprises. Model outputs are presented with a yearly time step, but within each year the model takes into account the labor needs and supply at a monthly scale. The workload constraint indicator then reflects the number of adaptations that farmers could make when managing the system:

$$Workload\ Constraint\ Indicator = \frac{1}{T} \sum_1^T 1 - \frac{1}{2} \left(\frac{WL_v(t)}{WR_v(t)} + \frac{WL_f(t)}{WR_f(t)} \right) \quad (7)$$

where $WL_v(t)$ is the workload effectively allocated to vegetables at year (t) and $WR_v(t)$ is the workload requirement for vegetables at year (t).

In order to study the temporal dynamics of mixed systems, we modeled the combination of three market gardening crop rotation types and three fruit tree portfolios (labelled respectively A, B and C in Fig. 2). The combination of these three strategies per enterprise generates nine scenarios. In each scenario, the two controls presented in Fig. 1, $U[0]$ and $U[1]$ can vary: $U[0]$, the relative area of fruit trees over vegetables is a continuous variable that ranges between 0.1 and 0.9. $U[1]$, the allocation of working time is a continuous variable

that ranges between 0 and 1 (i.e. between a systematic prioritization of working time towards market gardening to fruit trees).

As a first step, we simulated 10,000 random tree and crop portfolios in which the crop rotation and the controls described above are chosen randomly. In a second step, due to computation limitations, we modelled the nine contrasted scenarios described above, screening in detail controls $U[0]$ and $U[1]$ with 30 steps each. All computations were performed with Python 3.8.1 (www.python.org/), graphical outputs were produced alternatively with Python and R software 3.6.0 (<https://cran.r-project.org>). Model source code is available in Appendix C.

3. Results

3.1. Fruit tree dynamics

The collective experts' knowledge sharing workshop, completed with additional expert interviews, made it possible to describe six main species of fruit trees most cultivated in the South-East of France: Apple (*Malus domestica*), Peach (*Prunus persica*), Pear (*Pyrus communis* L.), Apricot (*Prunus armeniaca*), Cherry (*Prunus avium*) and Prune (*Prunus domestica*). The dynamics (Fig. 3) illustrate the potential yield of each fruit trees according to three levels of workload allocation: (i) optimal investment; (ii) minimal investment; (iii) the intermediate scenario. At this stage, two types of fruit trees can be distinguished: those that require a high investment to produce (Fig. 3c, d, f), and the ones that are less sensitive to a lower maintenance and that can produce in the long term despite suboptimal management (Fig. 3a, b, e). Fruit tree species also differ in the timing of management and therefore in the dates on which workload conflicts may arise. These characteristics are important features to take into account in the design of an MFV system and will greatly influence the dynamics of the system in the long run.

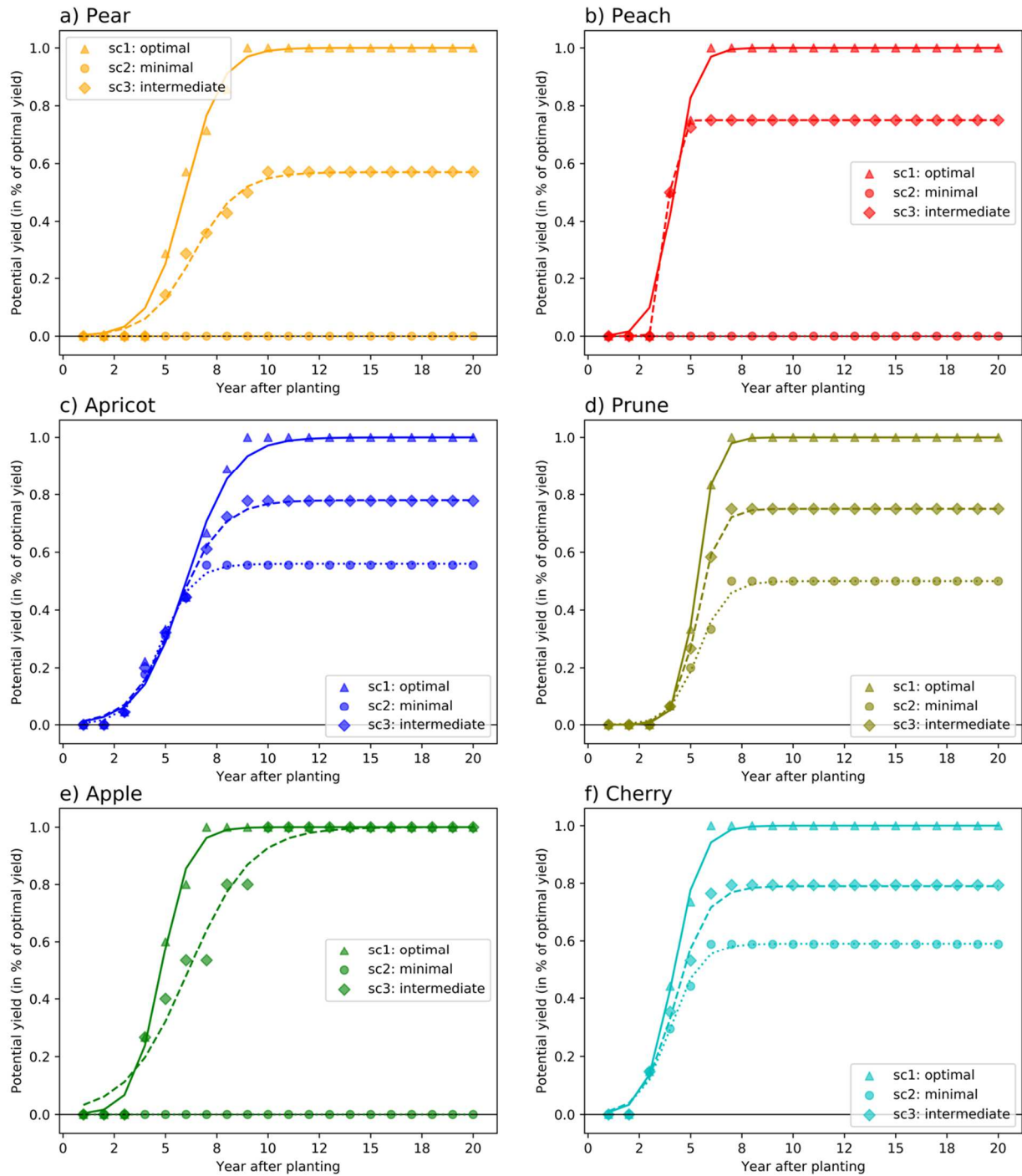


Fig. 3. Expert knowledge-based characterization of the dynamics of six important fruit trees over time according to three contrasted scenarios: (1) optimal investment; (2) moderate investment and (3) minimum investment (Cf. §2.4).

3.2. Crop rotation and workload allocation

As a first step, we modelled 10,000 random portfolios of 10 crops. Each portfolio is a random combination of fruit tree and vegetable enterprises, and a random workload allocation

between both enterprises. From these simulations, inter-annual average and standard deviation of gross margin were calculated (Fig. 4). At this stage, the average annual gross margin does not show clear trends, but we can observe that standard deviation of AGM is mainly driven by the relative share of each enterprise in the crop rotation.

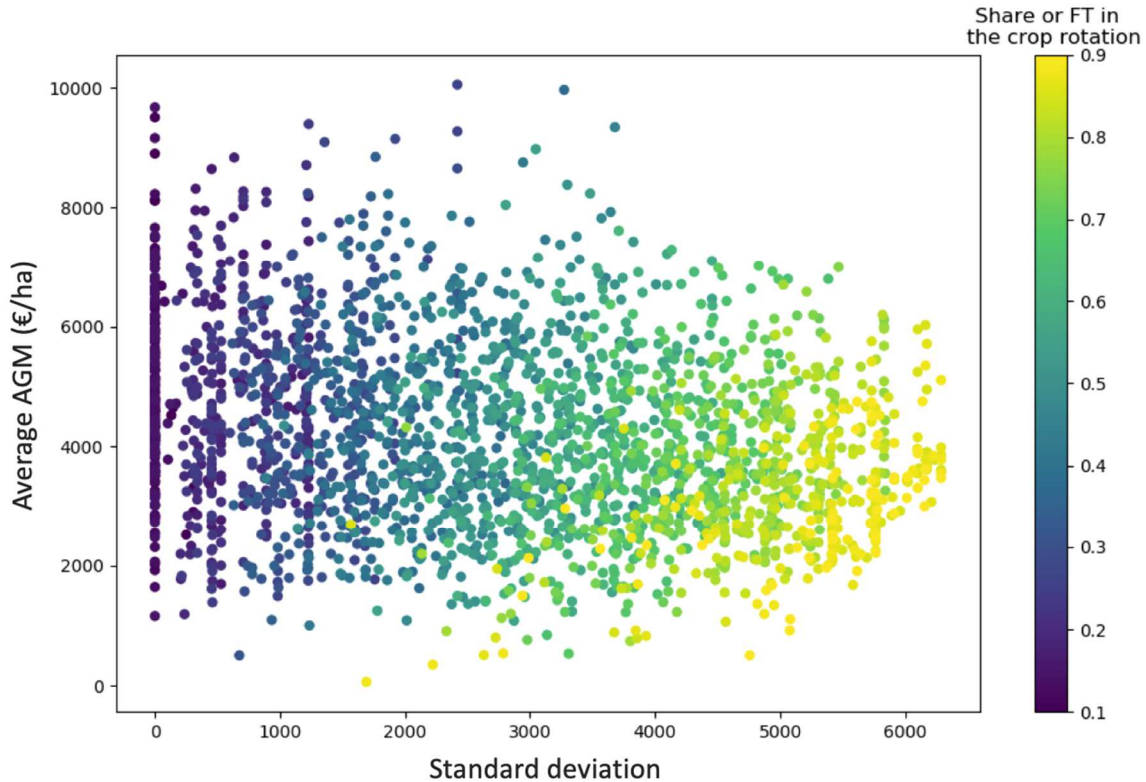


Fig. 4. Model-derived average annual gross margin and its inter-annual standard deviation from both orchard and market gardening enterprises, relative share of each enterprise in the crop rotation. FT: fruit trees; AGM: Annual Gross Margin.

The workload constraint indicator provides an indication of the ratio between the working time required by a given crop rotation and the work time available. This reflects the notion of feasibility (or unfeasibility) of a crop rotation, and whether adjustments are needed in work organization over the duration of trees. The measurement of workload constraints for the 10,000 random portfolios shows that the indicator is > 0 for 87.2% of the scenarios, which implies that adaptations are necessary for all these scenarios (Fig. 5). The number of adaptations needed increased with the prioritization of one or another of the crops. This indicates that lower constraints on working time are found for intermediate strategies, balancing trees and vegetables within the system. Furthermore, workload constraints decrease with the relative share of fruit in the crop rotation, highlighting the existence of a trade-off between AGM standard deviation and workload constraint.

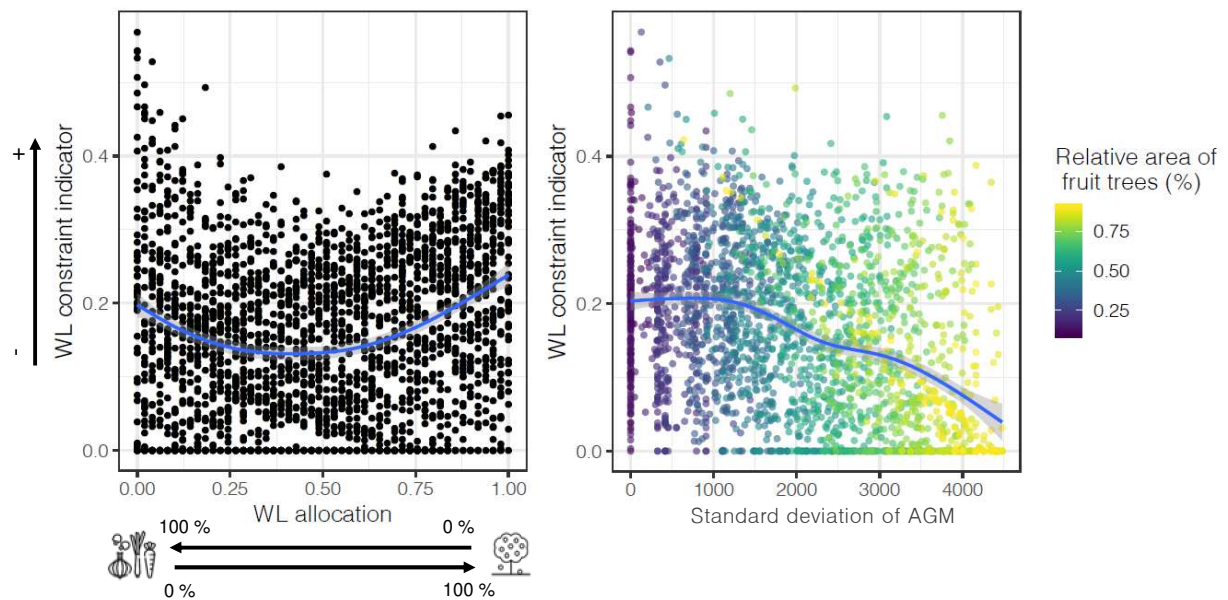


Fig. 5. Workload constraint indicator as a function of (left) workload allocation between both enterprises; (right) standard deviation of annual gross margin. The blue curve displays the smoothed conditional mean. The color gradient represents the relative area of fruit trees in the crop rotation. WL: workload; AGM: annual gross margin.

3.3. Trade-offs between short-term and-long term objectives

To deepen the analysis of trade-offs between short-term and long-term objectives, we investigated the combination of the two means of control (workload allocation and share of each enterprise) on system dynamics, in contrasted situations. Three distinct vegetable crop rotations and three distinct fruit tree portfolios were selected (labelled respectively A, B and C in Fig. 2). The combination of these three strategies per enterprise generates nine scenarios (Fig. 6). The relation between the workload allocation and the relative share of each enterprise in the crop rotation shows that overall a better average annual gross margin (AGM) is obtained with a higher proportion of vegetables (x-axis) and higher workload allocated to vegetables (y-axis) (Fig. 6a). Nevertheless, for intensive market gardening (vegs = C), it seems that a combination of a significant part of fruit trees with an allocation of working time towards fruit trees brings satisfactory results. The workload constraint indicator provides additional information (Fig. 6b). For low-intensity vegetable crop rotation (Vegs = A), the overall trend is that high NPVs are associated with low workload constraints. However, for intermediate and intensive vegetable crop situations (Vegs = B and C), the increased part of fruit trees in the crop

273 rotation makes it possible to maintain high levels of profitability while decreasing workload
274 constraints.

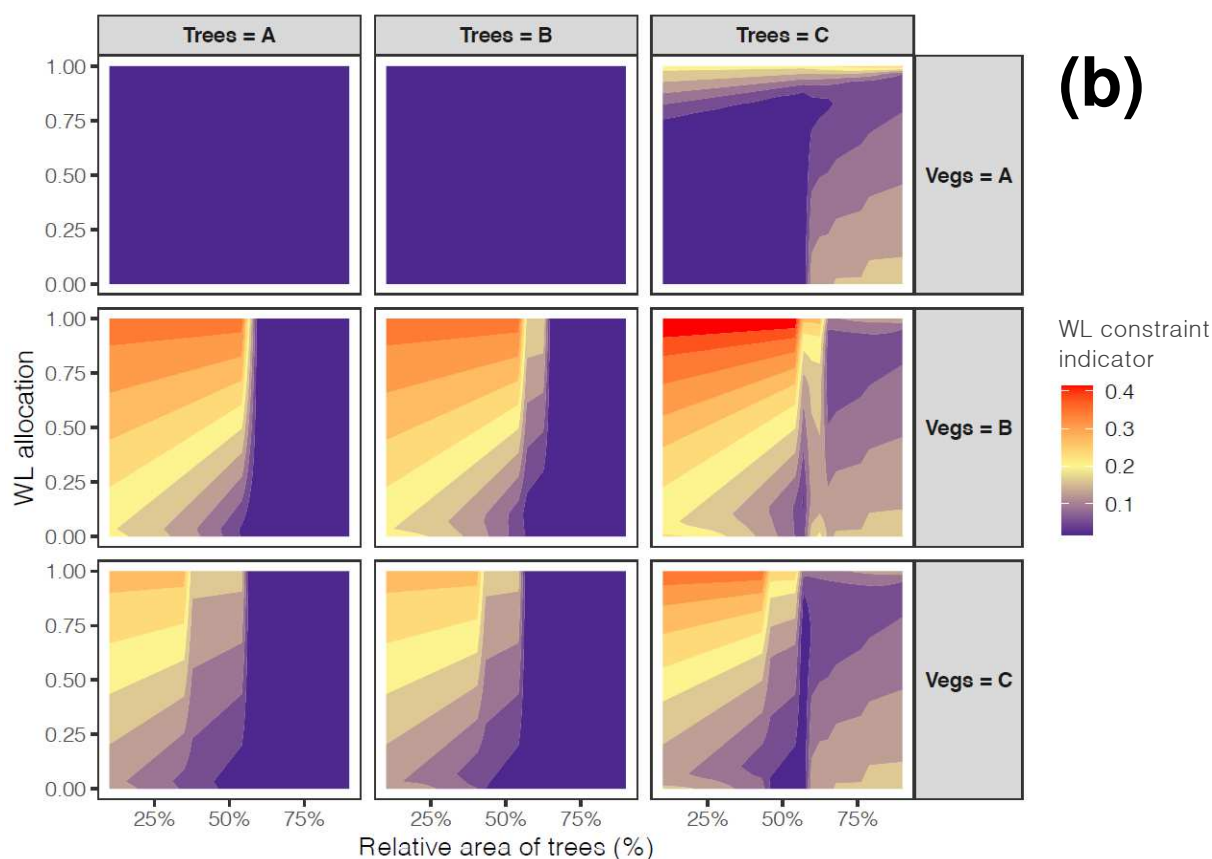
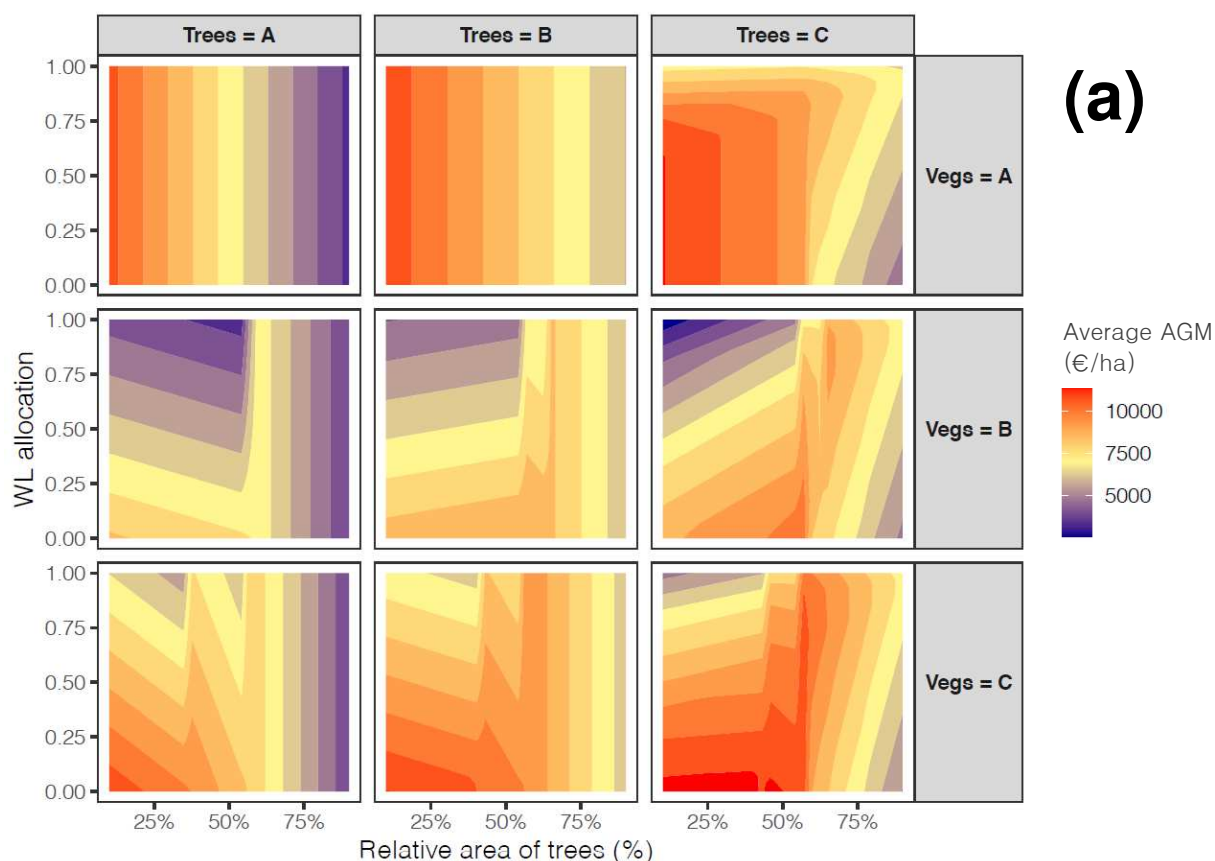


Fig. 6. Model-derived (a) average annual gross margin and (b) workload constraint indicator, according to nine scenarios combining fruit trees and vegetable crops. Trees: Fruit trees portfolio. Vegs: vegetable crop rotation. A, B, C respectively refer to extensive, intermediate and intensive crop rotation. Each scenario was modeled with controls of 30 steps each. WL: workload. AGM: annual gross margin.

These results provide a first insight into what different combinations of controls can achieve under very distinct scenarios. However, it is important to further analyze these characteristics, particularly their evolution over time. Over twenty years, we analyzed the average AGM as a function of the share of each enterprise in the crop rotation (Fig. 7a). To compare different values of the control $U[0]$, we plotted the net present value (NPV) difference between three values of $U[0]$: 0.1, 0.5, and 0.9. The difference between these three $U[0]$ values is given pair by pair (Fig. 7b, c, d).

The results show that crop rotations including a larger share of vegetable crops lead systematically to a better short-term productivity. However, the long-term profitability shows mixed features. In Fig. 7b, for instance, if we consider the difference between strategies promoting vegetables (FT_{\min}) and intermediate strategies (FT_{interm}), we can observe two tipping points. First, the gap between both strategies is compensated from the fifth year onwards, and FT_{interm} becomes more effective on an annual basis. Second, the NPV over the entire period indicates that the FT_{interm} strategy is generally more profitable (second switchover at 10 years after planting). In Fig. 7c, the comparison between FT_{\min} and FT_{\max} shows that both strategies have a similar NPV over 20 years, but FT_{\min} is more profitable in the first 6 years. Finally, comparing FT_{interm} and FT_{\max} (Fig. 7d) shows that the intermediate strategy is always more profitable than a strategy promoting fruit trees.

This indicates that in the long term, a strategy favoring intermediate share of fruit trees can be more desirable than a strategy promoting one or another enterprise. However, strategies implying large shares of fruit trees require being able to cope with several successive years of low (or even negative) ANPV, either by accepting a lower income in the first years, or through a larger starting capital. This underlines the importance of analyzing not only the overall NPV but also its dynamics through time, as it is likely to fluctuate significantly.

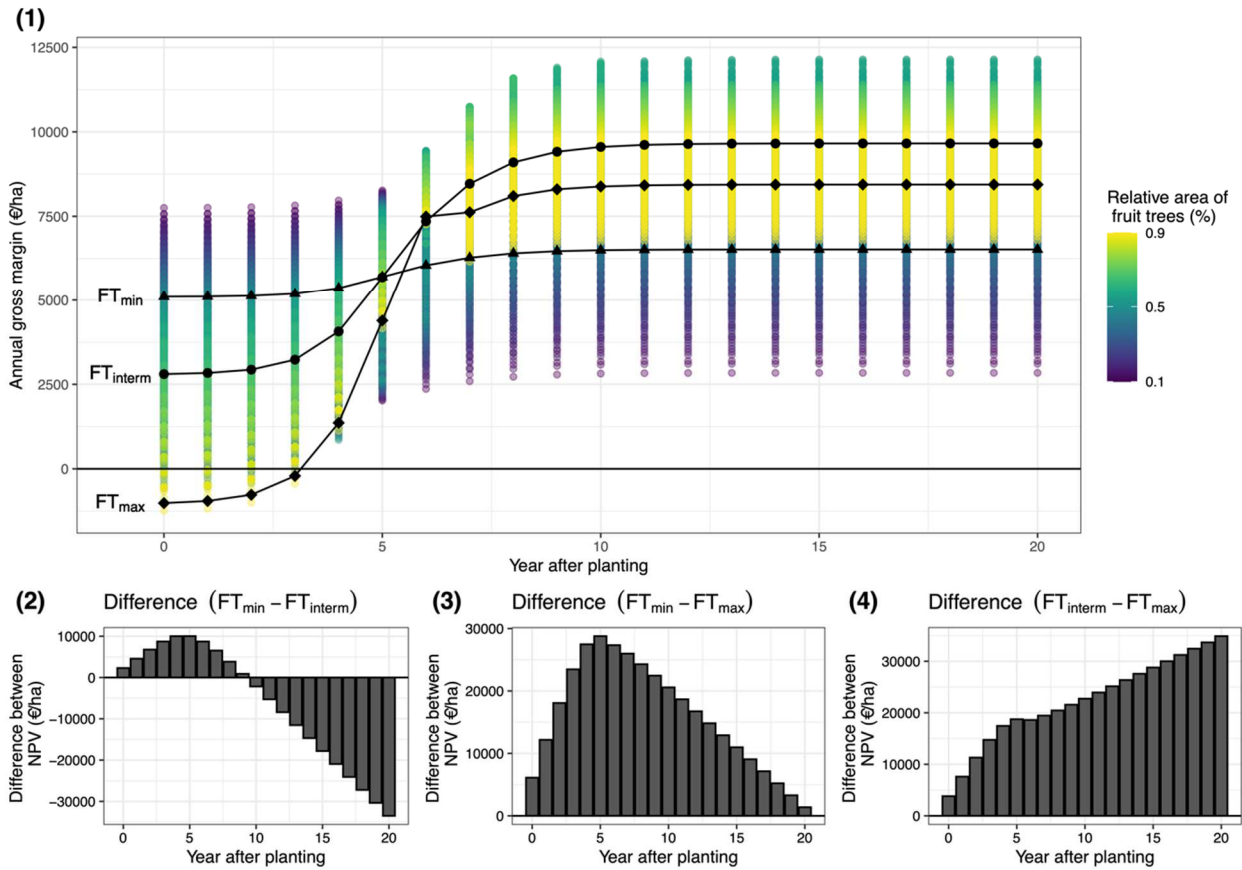


Fig. 7. (1) Evolution of the annual gross margin in the scenario combining intermediate vegetables scenario (Vegs = B, corresponding to an intermediate labor- and remuneration-intensive strategy) and intensive fruit trees scenario (Trees = C, corresponding to a high labor- and remuneration-intensive strategy) according to the relative share of each enterprise in the crop rotation ($U[0]$). Three contrasted values of $U[0]$, 0.1 (\blacktriangle), 0.5 (\bullet) and 0.9 (\blacklozenge) are compared pair by pair: (2) $FT_{min} - FT_{interm}$; (3) $FT_{min} - FT_{max}$ and (4) $FT_{interm} - FT_{max}$. AGM: Annual Gross Margin. NPV: Net Present Value.

4. Discussion

4.1. Model strengths and limitations

Mixed fruit tree-vegetable systems, which correspond to the combination of fruit trees and vegetable crops within a farming system, are currently undergoing strong development in France and other parts of Europe. However, since this is a relatively recent dynamic, empirical data on these systems are very rare and biological processes are still very uncertain (Imbert et al., 2020; Lauri et al., 2019). In the present study, we built a simple model of mixed fruit tree vegetable (MFV) system to assess its main properties through time. The approach presented in

this study has been to combine in a dynamic way quantitative elements from both fruit trees and vegetables with qualitative and quantitative elements from expert knowledge to develop a model of MFV systems at a one-hectare scale. This model was dynamically implemented to (i) explore different management strategies in MFV systems and (ii) to dynamically predict long-term fruit tree and vegetable crops dynamics under competitive conditions on workload between both enterprises. This is, to our knowledge, the first attempt to model dynamics of MFV systems. Existing dynamic bio-economic model applications of mixed trees and crops systems do not consider the existence of two annually productive plants (van der Werf et al., 2007; van Noordwijk and Lusiana, 1999) and they also rarely take into account labor constraints linked to the presence of other enterprises (but see Graves et al., 2011). However, these models take better account of interactions for resources other than labor (mainly biological interactions for water, nutrients and light). A model including all these interactions could be even more relevant, although relatively complex to implement in a purely deterministic way.

The use of a dynamic analytical framework applied to MFV systems made it possible to highlight the relation between different dimensions of system performance. The simulation of various characteristic scenarios also allows to show the relationships between the share of each enterprise in the crop rotation (fruit trees and vegetables), the workload allocation and the bio-economic performance of the system. Our results indicate that specialized market gardening enterprise has an overall better short- and long-term profitability per hectare (but not necessarily per working hour) than specialized fruit trees. Nevertheless, mixed systems composed of roughly equivalent shares of fruit trees and vegetable crops make it possible to decrease workload constraints while maintaining a high level of profitability. In addition, these intermediate situations can lead to better profitability in the long term, but require addressing both short- and long-term objectives, and the ability to cope with several consecutive years of lower income. The issue of uncertainty into long-term performance projections of agroforestry systems has recently been highlighted in tropical fruit-based agroforestry systems (Do et al., 2020) and seems to be a recurring obstacle to the adoption of such systems.

Due to the simplicity of its individual components, the overall model was still manageable in terms of complexity and number of inputs required. This deliberately simple model makes it possible to model a large panel of situations. It has nevertheless some limitations that deserve to be discussed in more details. A first limit of our approach is that the model does not take into account some important but unknown tree-crop biological interactions. In mixed fruit tree – vegetable systems, crops can be organized in intercropping or

agroforestry design, where crops have biological interactions with each other (Paut et al., 2020). These interactions may lead to a different overall yield and profitability, but may also influence the yields of both vegetables and fruit trees in a dynamic way (Burgess et al., 2019; Paul et al., 2017). In view of the current state of the literature on these systems, such components have not been included in the analysis, but it would be relevant to integrate them for further development of our model (Van Vooren et al., 2016).

Another limitation to our approach is that the model was deterministic and did not capture the uncertainty on parameter values. In fruit production, in particular, some key elements such as alternate bearing or climatic factors can affect inter-annual yield variability (Beattie and Folley, 1977). These sources of uncertainty are all the more justified in MFV systems as there is very little knowledge about the development of fruit trees under suboptimal management conditions. The introduction of stochasticity on key parameters (e.g., fruit tree yields) would be an approach to overcome these limitations. In this perspective, dynamic stochastic modelling approaches are very useful for characterizing the management flexibility of a system in a highly fluctuating and uncertain environment (Accatino et al., 2014; Do et al., 2020; Sabatier et al., 2015).

4.2. Implications and perspectives

Our approach makes it possible to quantify dynamically the annual profitability of mixed fruit tree-vegetable farming systems. Combined with the characterization of implications in terms of labor constraints at different times of the year, it allowed highlighting determining factors of success at the scale of a one-hectare plot. The integration of farm fixed costs may in turn be used for a global farm analysis (García de Jalón et al., 2018; Graves et al., 2011, 2007).

Finally, as with other integrated systems, an important aspect that would require further investigations is the dynamic and adaptive system management (Bell and Moore, 2012; Hendrickson et al., 2008). In our approach, we simulated scenarios where controls were defined as strategies for the entire cycle duration. However, it has been shown that adaptive management is a crucial factor to integrate in the analysis of agroecological systems (Catalogna et al., 2018). In MFV systems, trees are planted and fixed in the system but vegetable crop rotation may vary over time. The management needs to be adapted to structural and functional changes that these systems undergo over time (Léger et al., 2019). Trade-offs that relate to the immediate provision of the production service (in our case, market gardening) may be to the detriment of other services in the future (e.g., fruit production). These trade-offs over time have

a decisive impact on the biological dynamics of the agroecosystem. Many natural processes, such as those affecting tree training, occur at such a rate that several years may pass before significant effects are perceived by the farmer (Lauri et al., 2019, 2016). The consequences of these trade-offs are then borne with a time lag. A useful method to capture the evolution of a dynamically managed system is viability theory (Aubin, 1991). This mathematical framework makes it possible to study the evolution of dynamical systems under constraints on the system states and controls. Its recent applications to natural resource management have proved to be particularly relevant on livestock systems (Sabatier et al., 2017; Tichit et al., 2004) or silviculture (Domenech et al., 2011) and would be particularly relevant for improving our approach.

5. Conclusion

Our model was a first attempt to analyze mixed fruit tree vegetable (MFV) systems. We developed a dynamic bio-economic model to investigate the consequences of farmers' management decisions in terms of crop rotation and workload allocation on the dynamics of MFV systems. Using this dynamic approach based on states and controls, we simulated management strategies for both market gardening and orchard, and assessed their impact on the long-term dynamics of the system. The results made it possible to illustrate the consequences of different types of trade-offs between management objectives when making decisions in the steering of these systems, taking into account uncertainty linked to the lack of knowledge about these processes. These results highlight that the integration of fruit trees into a market gardening system can maintain a high level of profitability, while at the same time being a driver of flexibility. However, MFV systems require coping with several years of lower income due to the delay of fruit production. Further research will now be needed to better understand the processes underlying MFV systems and their dynamics in different management configurations.

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How to reconcile short-term and long-term objectives in mixed farms? A dynamic model application to mixed fruit tree - vegetable systems

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Graphical abstract

