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1 **How to reconcile short-term and long-term** 2 **objectives in mixed farms? A dynamic model** 3 **application to mixed fruit tree - vegetable** 4 **systems**

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10 **Abstract**

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

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

32

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

34

35 **1. Introduction**

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

49 The existing literature on MFV deals mainly with their conception (Sieffert et al.,
50 2014; Warlop and Castel, 2016), or consists of detailed descriptive analyses (Léger et al., 2018;
51 Pantera et al., 2018). While this work is important, it leaves farmers somewhat lacking
52 regarding the management of these systems, as the interactions between agro-ecological
53 processes and management actions are not taken into account. However, the management of
54 MFV is particularly challenging for two main reasons. The first reason is linked to the great
55 complexity of these systems, since they add up the intrinsic difficulties of two very demanding
56 systems – orchard and market gardening – to which are added the difficulties linked to the

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

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

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

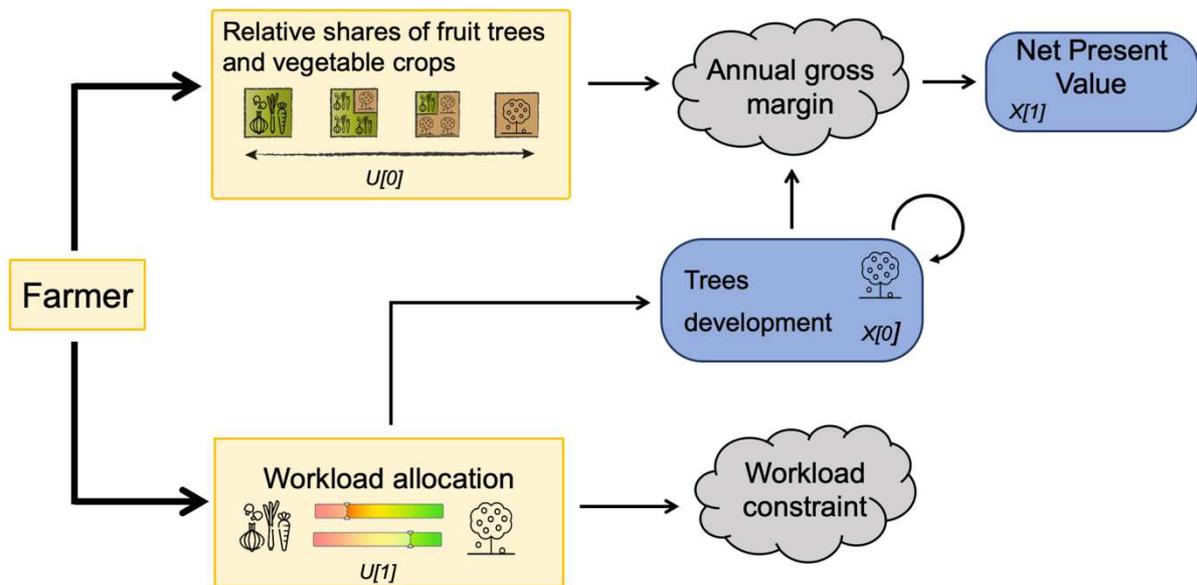
78 In the present study, we built a simple dynamic model of a mixed fruit tree-vegetable
79 farming system making it possible to assess its main properties through time. This model is
80 then implemented to explore different management strategies in MFV farming systems. The
81 ultimate goal of our model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

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

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.

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

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**

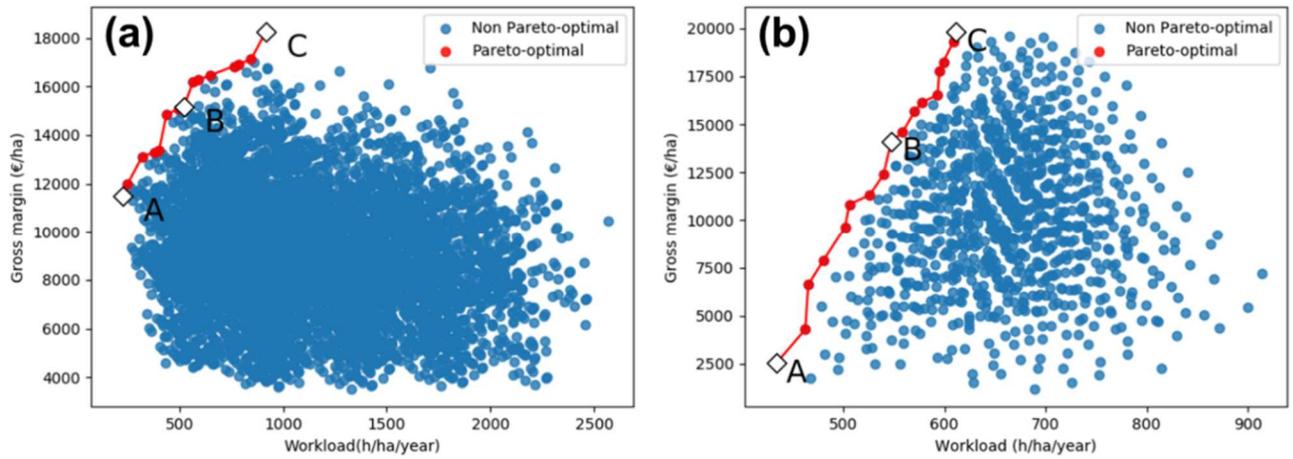
125 The market gardening sub-model consists of an intra-annual rotation of vegetable
 126 crops, where each crop represents an equivalent $1/N_v$, N_v being the total number of crops. Each
 127 vegetable crop is defined by a gross margin (VGM) and a workload requirement (WR).
 128 Depending on the workload 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):

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

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

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

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



145
 146 **Fig. 2.** Gross margin as a function of workload for all possible portfolios of (a) 5 vegetable
 147 crops and (b) at least 3 fruit tree species.

148

149 2.4. Orchard sub-model

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

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

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

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

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

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

177

178 2.5. Performance indicators and simulations

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

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

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

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

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

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

193 where $WL_v(t)$ is the workload effectively allocated to vegetables at year (*t*) and
 194 $WR_v(t)$ is the workload requirement for vegetables at year (*t*).

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

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

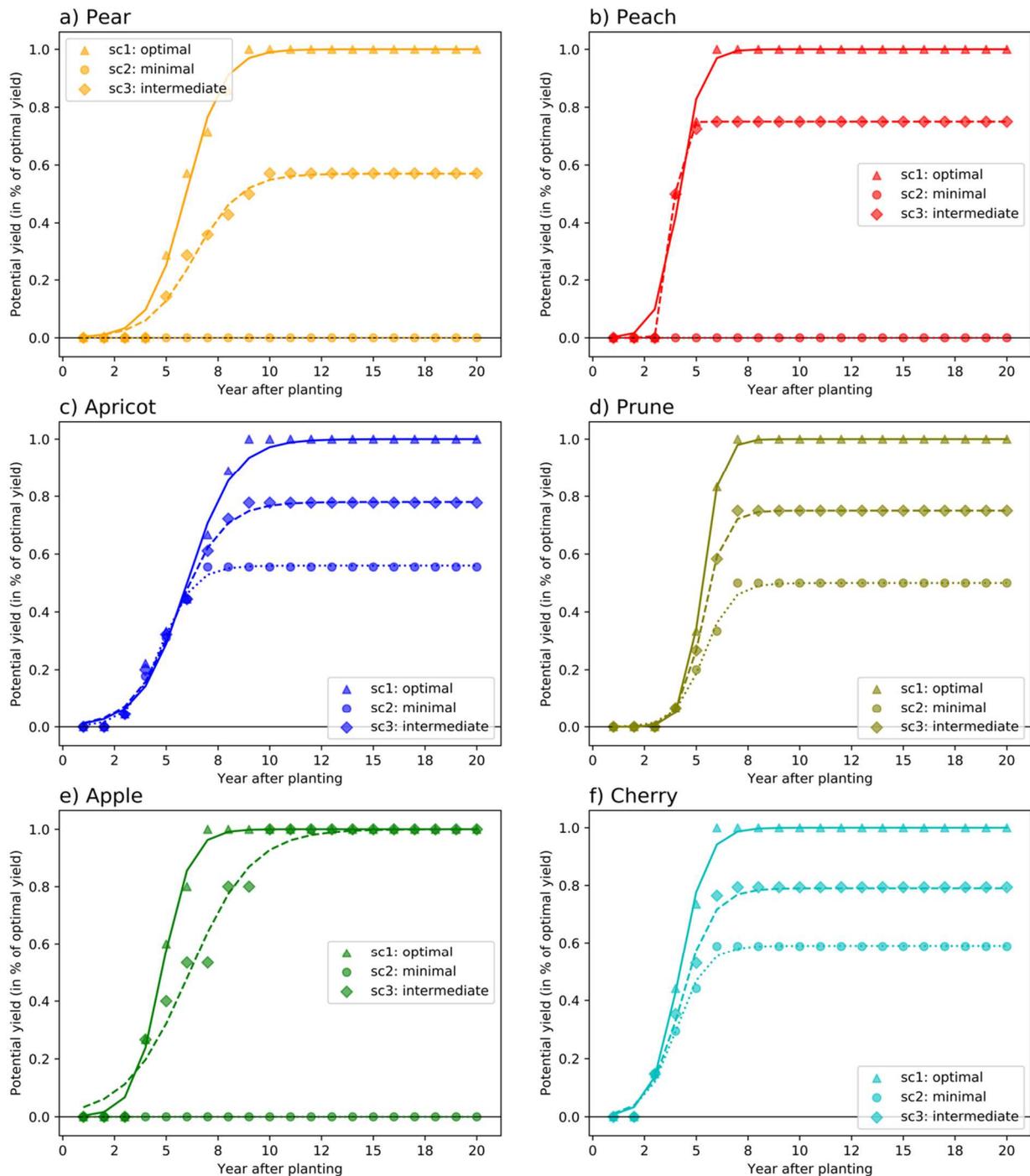
203 As a first step, we simulated 10,000 random tree and crop portfolios in which the crop
204 rotation and the controls described above are chosen randomly. In a second step, due to
205 computation limitations, we modelled the nine contrasted scenarios described above, screening
206 in detail controls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

209

210 **3. Results**

211 **3.1. Fruit tree dynamics**

212 The collective experts' knowledge sharing workshop, completed with additional
213 expert interviews, made it possible to describe six main species of fruit trees most cultivated in
214 the South-East of France: Apple (*Malus domestica*), Peach (*Prunus persica*), Pear (*Pyrus*
215 *communis* L.), Apricot (*Prunus armeniaca*), Cherry (*Prunus avium*) and Prune (*Prunus*
216 *domestica*). The dynamics (Fig. 3) illustrate the potential yield of each fruit trees according to
217 three levels of workload allocation: (i) optimal investment; (ii) minimal investment; (iii) the
218 intermediate scenario. At this stage, two types of fruit trees can be distinguished: those that
219 require a high investment to produce (Fig. 3c, d, f), and the ones that are less sensitive to a
220 lower maintenance and that can produce in the long term despite suboptimal management (Fig.
221 3a, b, e). Fruit tree species also differ in the timing of management and therefore in the dates on
222 which workload conflicts may arise. These characteristics are important features to take into
223 account in the design of an MFV system and will greatly influence the dynamics of the system
224 in the long run.



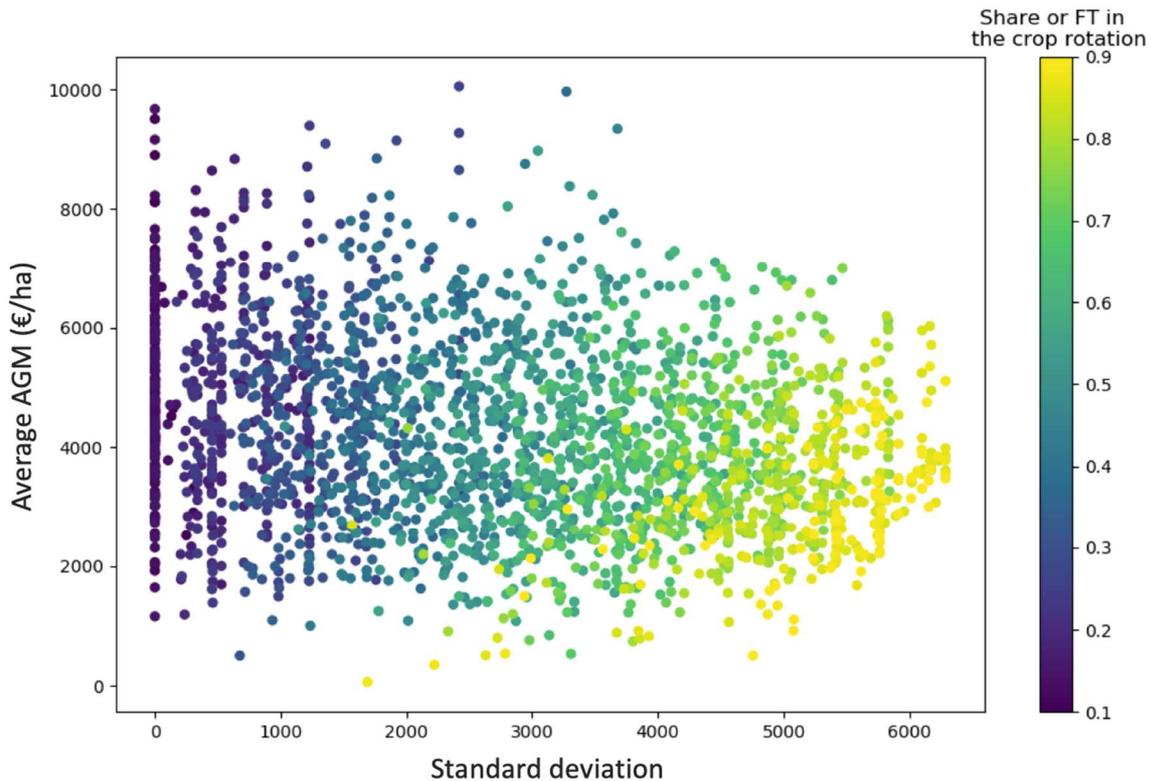
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226 **Fig. 3.** Expert knowledge-based characterization of the dynamics of six important fruit trees
 227 over time according to three contrasted scenarios: (1) optimal investment; (2) moderate
 228 investment and (3) minimum investment (Cf. §2.4).

229 **3.2. Crop rotation and workload allocation**

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

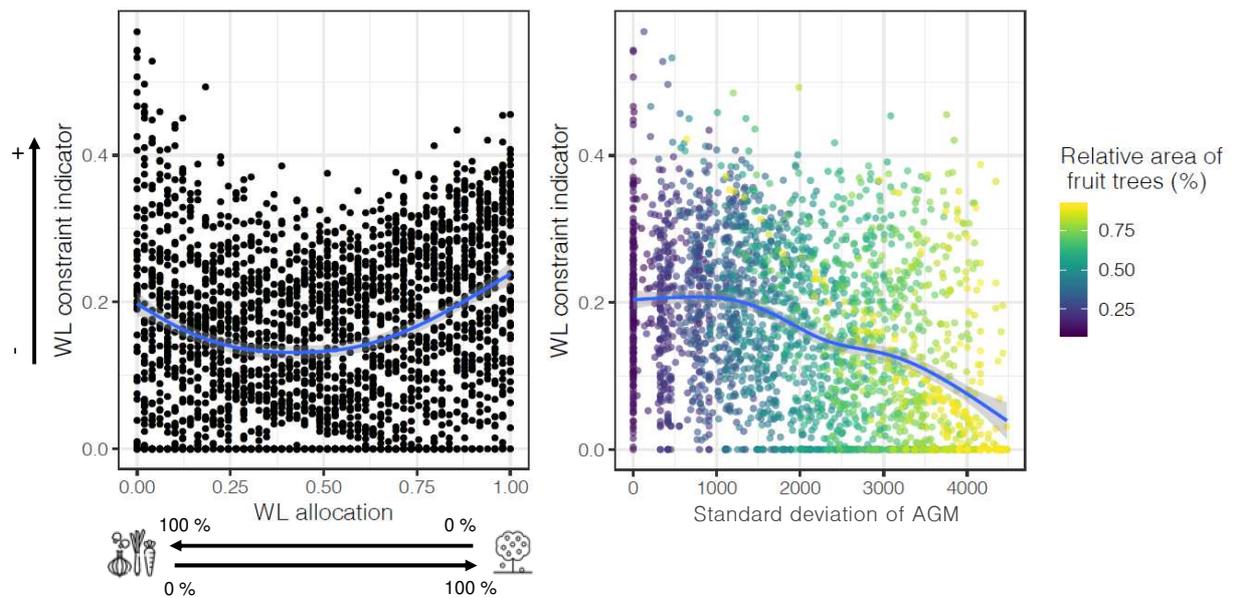
232 between both enterprises. From these simulations, inter-annual average and standard deviation
233 of gross margin were calculated (Fig. 4). At this stage, the average annual gross margin does
234 not show clear trends, but we can observe that standard deviation of AGM is mainly driven by
235 the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



236

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

240 The workload constraint indicator provides an indication of the ratio between the
241 working time required by a given crop rotation and the work time available. This reflects the
242 notion of feasibility (or unfeasibility) of a crop rotation, and whether adjustments are needed in
243 work organization over the duration of trees. The measurement of workload constraints for the
244 10,000 random portfolios shows that the indicator is > 0 for 87.2% of the scenarios, which
245 implies that adaptations are necessary for all these scenarios (Fig. 5). The number of
246 adaptations needed increased with the prioritization of one or another of the crops. This
247 indicates that lower constraints on working time are found for intermediate strategies,
248 balancing trees and vegetables within the system. Furthermore, workload constraints decrease
249 with the relative share of fruit in the crop rotation, highlighting the existence of a trade-off
250 between AGM standard deviation and workload constraint.



251

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

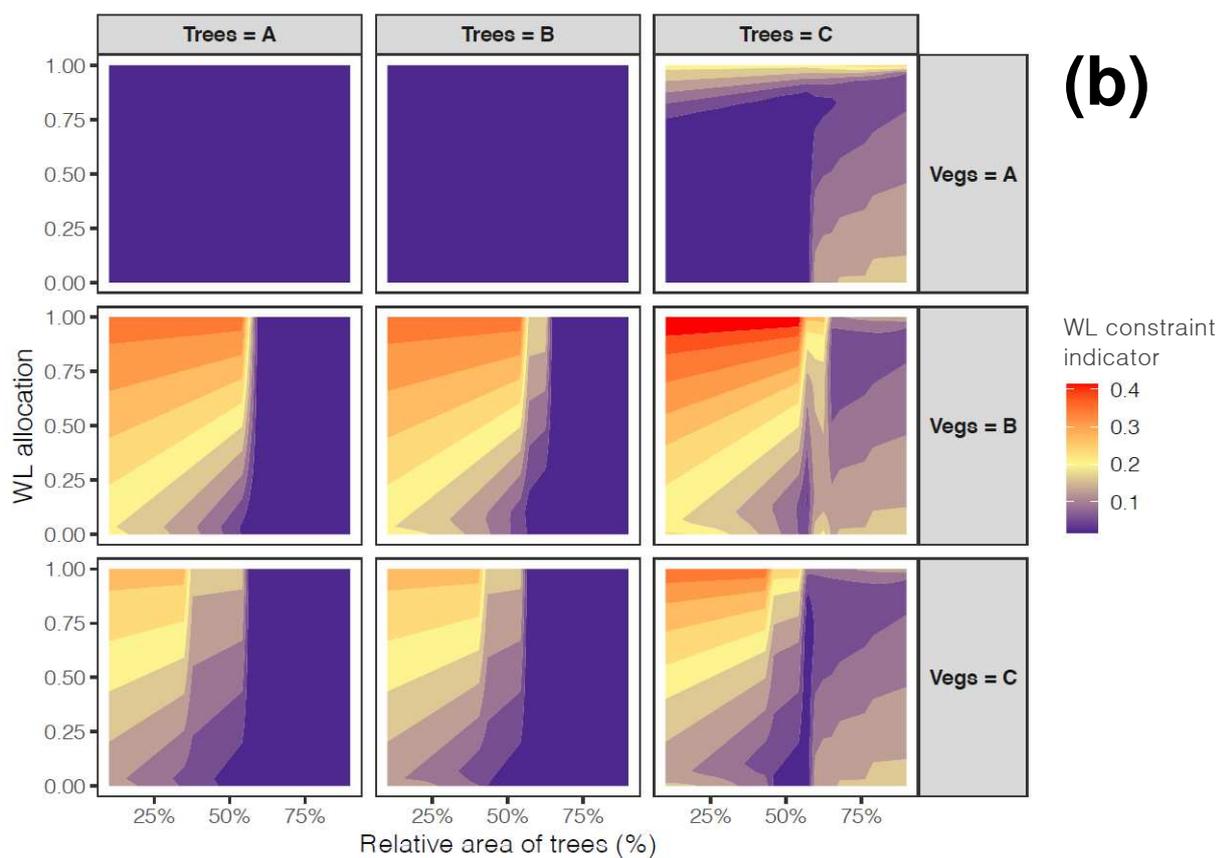
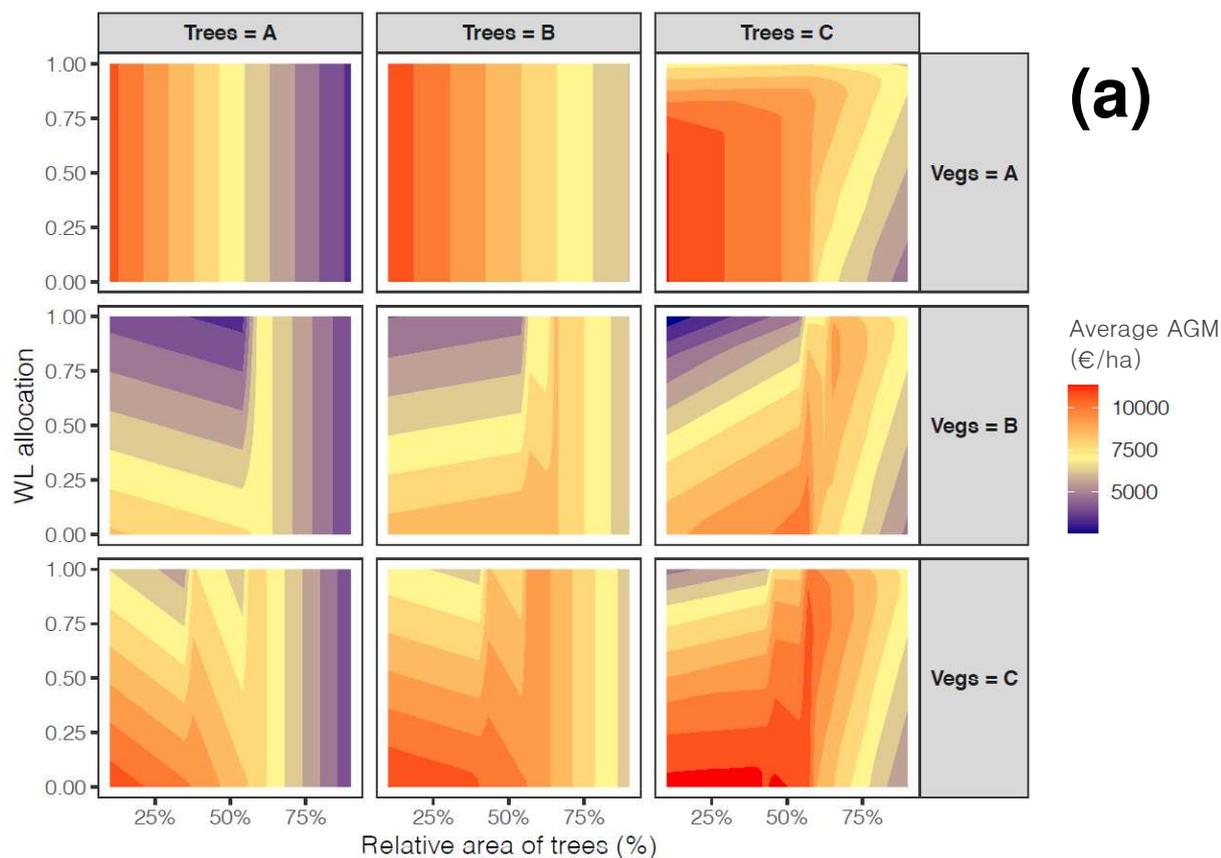
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257 3.3. Trade-offs between short-term and-long term

258 objectives

259 To deepen the analysis of trade-offs between short-term and long-term objectives, we
 260 investigated the combination of the two means of control (workload allocation and share of
 261 each enterprise) on system dynamics, in contrasted situations. Three distinct vegetable crop
 262 rotations and three distinct fruit tree portfolios were selected (labelled respectively A, B and C
 263 in Fig. 2). The combination of these three strategies per enterprise generates nine scenarios
 264 (Fig. 6). The relation between the workload allocation and the relative share of each enterprise
 265 in the crop rotation shows that overall a better average annual gross margin (AGM) is obtained
 266 with a higher proportion of vegetables (x-axis) and higher workload allocated to vegetables (y-
 267 axis) (Fig. 6a). Nevertheless, for intensive market gardening (vegs = C), it seems that a
 268 combination of a significant part of fruit trees with an allocation of working time towards fruit
 269 trees brings satisfactory results. The workload constraint indicator provides additional
 270 information (Fig. 6b). For low-intensity vegetable crop rotation (Vegs = A), the overall trend is
 271 that high NPVs are associated with low workload constraints. However, for intermediate and
 272 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.



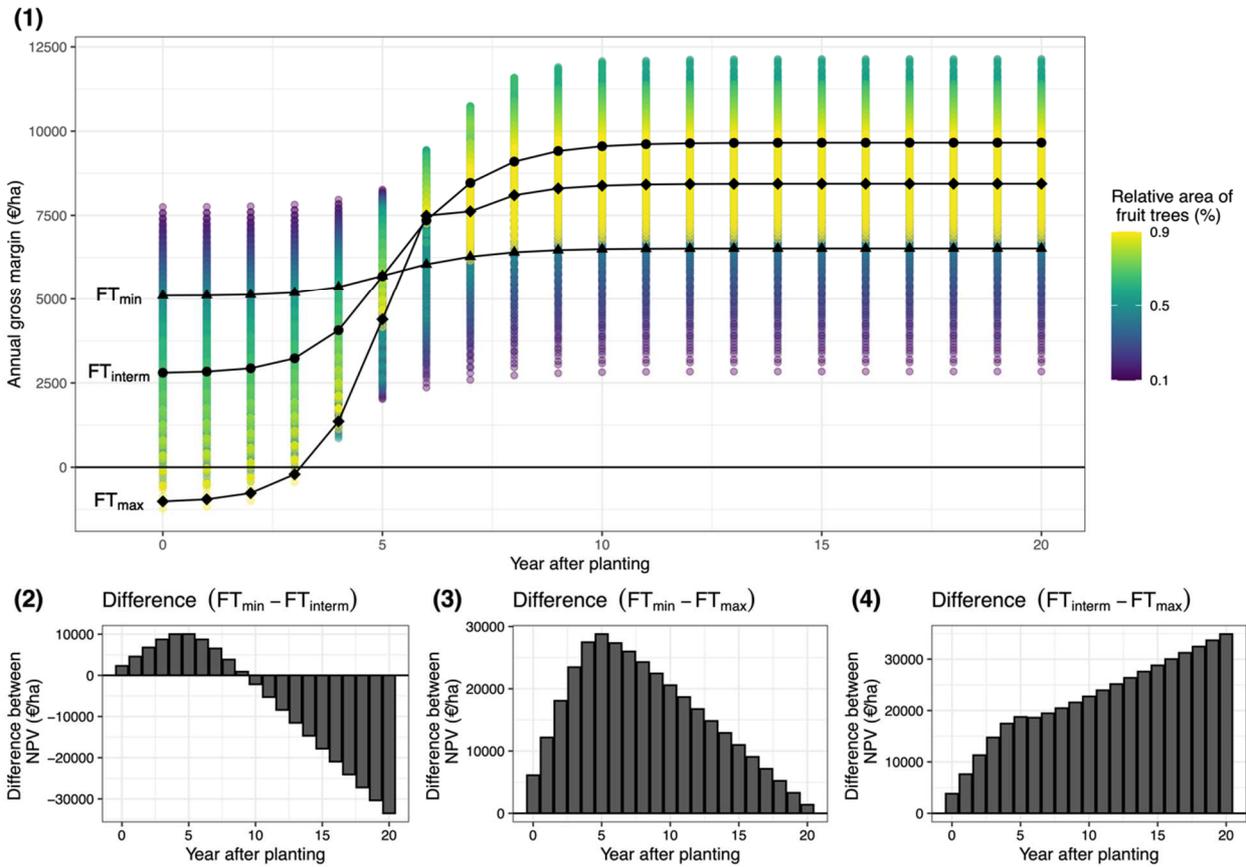
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276 **Fig. 6.** Model-derived (a) average annual gross margin and (b) workload constraint indicator,
 277 according to nine scenarios combining fruit trees and vegetable crops. Trees: Fruit trees
 278 portfolio. Vegs: vegetable crop rotation. A, B,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

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

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

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



305

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

313

314

315 4. Discussion

316 4.1. Model strengths and limitations

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

323 this study has been to combine in a dynamic way quantitative elements from both fruit trees
324 and vegetables with qualitative and quantitative elements from expert knowledge to develop a
325 model of MFV systems at a one-hectare scale. This model was dynamically implemented to (i)
326 explore different management strategies in MFV systems and (ii) to dynamically predict long-
327 term fruit tree and vegetable crops dynamics under competitive conditions on workload
328 between both enterprises. This is, to our knowledge, the first attempt to model dynamics of
329 MFV systems. Existing dynamic bio-economic model applications of mixed trees and crops
330 systems do not consider the existence of two annually productive plants (van der Werf et al.,
331 2007; van Noordwijk and Lusiana, 1999) and they also rarely take into account labor
332 constraints linked to the presence of other enterprises (but see Graves et al., 2011). However,
333 these models take better account of interactions for resources other than labor (mainly
334 biological interactions for water, nutrients and light). A model including all these interactions
335 could be even more relevant, although relatively complex to implement in a purely
336 deterministic way.

337 The use of a dynamic analytical framework applied to MFV systems made it possible
338 to highlight the relation between different dimensions of system performance. The simulation
339 of various characteristic scenarios also allows to show the relationships between the share of
340 each enterprise in the crop rotation (fruit trees and vegetables), the workload allocation and the
341 bio-economic performance of the system. Our results indicate that specialized market
342 gardening enterprise has an overall better short- and long-term profitability per hectare (but not
343 necessarily per working hour) than specialized fruit trees. Nevertheless, mixed systems
344 composed of roughly equivalent shares of fruit trees and vegetable crops make it possible to
345 decrease workload constraints while maintaining a high level of profitability. In addition, these
346 intermediate situations can lead to better profitability in the long term, but require addressing
347 both short- and long-term objectives, and the ability to cope with several consecutive years of
348 lower income. The issue of uncertainty into long-term performance projections of agroforestry
349 systems has recently been highlighted in tropical fruit-based agroforestry systems (Do et al.,
350 2020) and seems to be a recurring obstacle to the adoption of such systems.

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

357 agroforestry design, where crops have biological interactions with each other (Paut et al.,
358 2020). These interactions may lead to a different overall yield and profitability, but may also
359 influence the yields of both vegetables and fruit trees in a dynamic way (Burgess et al., 2019;
360 Paul et al., 2017). In view of the current state of the literature on these systems, such
361 components have not been included in the analysis, but it would be relevant to integrate them
362 for further development of our model (Van Vooren et al., 2016).

363 Another limitation to our approach is that the model was deterministic and did not
364 capture the uncertainty on parameter values. In fruit production, in particular, some key
365 elements such as alternate bearing or climatic factors can affect inter-annual yield variability
366 (Beattie and Folley, 1977). These sources of uncertainty are all the more justified in MFV
367 systems as there is very little knowledge about the development of fruit trees under suboptimal
368 management conditions. The introduction of stochasticity on key parameters (e.g., fruit tree
369 yields) would be an approach to overcome these limitations. In this perspective, dynamic
370 stochastic modelling approaches are very useful for characterizing the management flexibility
371 of a system in a highly fluctuating and uncertain environment (Accatino et al., 2014; Do et al.,
372 2020; Sabatier et al., 2015).

373 **4.2. Implications and perspectives**

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

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

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

399

400 **5. Conclusion**

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

415

416

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- 552

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

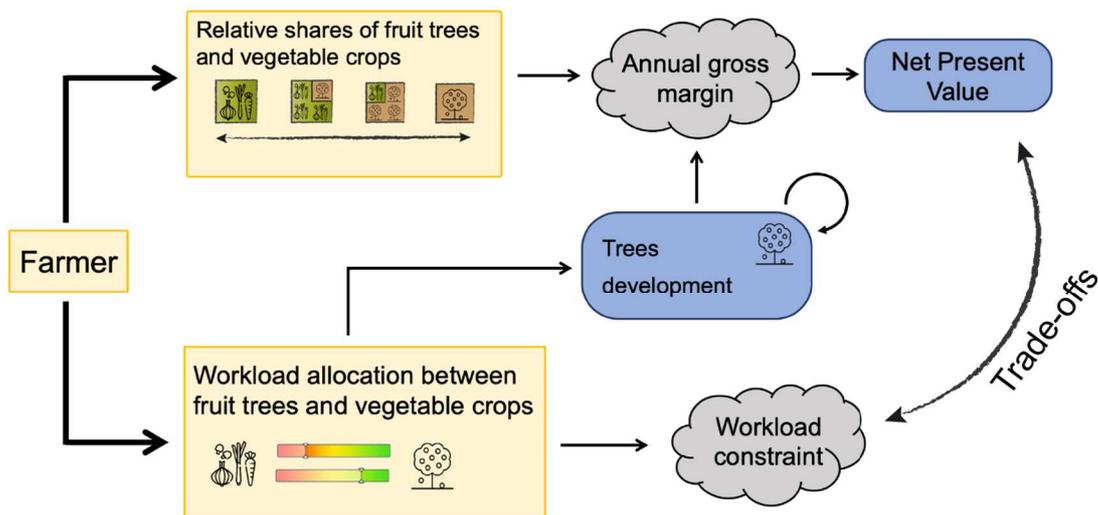
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10 **Graphical abstract**



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